TRANSMUTATION.

By Professor Kerr Grant, M.Sc., F.Inst.P.,
Professor of Physics, University of Adelaide.

The idea of converting one substance into another appears to be a very ancient one. Sir Edward Thorpe in his "History of Chemistry" propounds the view that it may have originated in the speculations of Greek philosophers on the mutual convertibility of what they believed to be the four primal elements, *viz.*, fire, air, water and earth.

Later, in the Middle Ages, the problem of transmutation narrowed down to that of converting the so-called baser metals, such as lead, tin, or copper, into the nobler, such as silver or gold; and the quest for an agent variously named the "philosopher's stone", the "grand magisterium", the "tincture" or the "quintessence", which would effect this transformation by some magical power, inspired the work of the mediæval alchemists.

The belief in the possibility of such transmutation was, no doubt, sustained by numerous instances of genuine chemical transformations, many of which were to all appearances of a far more fundamental character than the conversion of one metal into another.

Like many other magical agencies of a similarly mysterious nature, belief in the existence of which is far from extinct in our own day, the power of the philosopher's stone was not confined to a single purpose. It preserved health and prolonged life; it increased wisdom and virtue in him who possessed it; it was a universal solvent, and served not merely to transmute metals, but to produce precious gems.

Naturally, belief in the existence of a charm of such universal potency was associated with unlimited credulity on the one hand, and with fraud and imposture on the other. Yet it undoubtedly had this good result, that it served as a most powerful stimulus to chemical experimentation which led to a truer understanding of the nature of chemical change and, eventually, to the important discrimination between chemical elements and chemical compounds as we now make it. But when the real and profound nature of this distinction was finally appreciated an inevitable reaction set in against the erroneous beliefs and ridiculous pretensions of the alchemists so that the new generation of scientific physicists and chemists which arose within 17th, 18th and 19th centuries adopted an increasingly positive attitude of disbelief in the very possibility of transmutation of the elementary substances. The revival of the atomic theory of the ancient philosophers by Dalton in the first decade of the 19th century led naturally to the supposition that the various kinds of atoms were the primordial units out of which the universe was constructed in the first beginning, when the

> " . . . Heavens and Earth;
> Rose out of Chaos."

A saying recorded of Dalton himself makes interesting reading in the light of the " atom-smashing " achievements of the last few years.

Upholding the necessity of the law of multiple proportions in discussion with a friend, he said: " Thou knowest it must be so, for no man can split an atom." Some fifty years later, Sir John Herschel declared that the atom bore " the unmistakable stamp of the manufactured article ", and an even more profound and accurate thinker, he of whom his tutor at Cambridge declared that " it was impossible for that man to think incorrectly on matters of physical science ", stated his belief that the atoms of which all bodies are composed " can neither be stopped, nor broken in pieces, nor in any way destroyed or deprived of the least of their properties ".

It is permissible to suspect in these dogmatic affirmations an influence arising from certain preconceptions of a non-scientific character concerning the nature and the assumed mode of origin of the world. But it is also important to remember that ideas concerning the nature of the atom were still in no very essential particular different from the hard impenetrable particle of Democritus the Greek or Lucretius the Roman. The atom, as we now know, is a vastly more complicated structure than Dalton, or Herschel, or Clerk Maxwell conceived it to be. But for the unravelling of this complexity the methods of the older physics and chemistry of matter were utterly inadequate. In fact, the ordinary physical properties of matter: its weight and its inertia, its cohesion, its elasticity, its solidity or fluidity, even the remarkable variety of crystalline forms which it takes, do not necessitate an atomicity or discreteness of composition and, even if such a structure is postulated, it is sufficient to regard the atoms, as Boscovich did, as mere " centres of force ". The laws of analytical chemistry find a most satisfactory and simple explanation in Dalton's assumption of definite weights attaching to the various species of elementary atoms, but in this integral property there lies no hint of an inner complexity. The word "atom" retained its pristine significance.

It was the advent of spectroscopic analysis, revealing the multiplicity of the kinds of light-waves which a particular kind of atoms can emit, that first showed how totally inadequate was the picture of an atom as a minute structureless entity, and that, whatever it is, its internal structure must possess at least as many degrees of freedom as corresponded to these many modes of vibration. Even when this was realised, as it certainly was realised by such men as Maxwell and Kelvin, the conception of the complex atom continued to be based on a purely mechanical model, in which discrete parts possessing inertia were coupled together by elastic constraints.

Not until the closing decade of the 19th century, when J. J. Thomson proved that there existed atoms of negative electricity of invariable charge and mass which were constituents of every kind of metallic atom tested, did the electrical theory of the constitution of the atom—though roughly suggested far earlier by the facts of electrolytic transport, of contact-electricity, and of Maxwell's electro-magnetic theory of light—finally oust its mechanical rival.

This new conception of sub-atomic electrical particles which, as the phenomena of electrical discharge through rarefied gases clearly demonstrated, could be separated completely from the material atoms of which they formed a part, marked an epoch in scientific thought, for it shattered at a blow the ancient dogma of this indivisibility of the atom. It also gave the clue to the explanation of numerous electrical effects such as electrification by contact or by friction, electrolysis, ionisation of gases, the Zeeman effect, the Hall effect, and others.

With the acknowledgment of the real existence of electrons the old hard, impenetrable, indivisible atom "strong in single solidness" vacates the pages of science, and in its place, we have a more or less complex system of electrical particles held together in a structure normally definite for such atomic species, though capable to some extent at least of internal reorganisation and even of partial disruption. Since the atom is, normally, electrically neutral, it is clear that the total amount of negative electricity within it has to be balanced by precisely the same quantity of positive; but for many years no clue was found to the precise mode of internal arrangement.

A popular model for some years was that, proposed or upheld by Lord Kelvin, of a sphere of uniformly diffused positive electricity, in which the negative atoms were fixed "like plums in a pudding". Rutherford, in 1911, showed that such a structure was quite incompetent to explain the large deviations of path which the fast-flying α-rays from radium occasionally undergo when they pass through sheets of matter so thin that only a single atom is encountered at close quarters whereas, on the contrary, the observed law of scattering could be precisely calculated on the assumption that the whole of the positive electricity was concentrated within a space small in comparison with the size of this whole atom. This central core of the atom he termed the nucleus. It is the existence and the properties of this atomic nucleus which form fundamentals to an understanding of the real problems of atomic transmutation.

In 1912 the Danish physicist, Niels Bohr, confirmed and elaborated the nucleur atom-model of Rutherford, when, by a stroke of genius, he showed how this model could be made the basis of a remarkably complete explanation of the character of the light emitted by hydrogen gas in the atomic state. According to this "quantum" theory of radiation the outer electrons of an atom emit light only when, after having been displaced from their normal orbits to one of higher energy-level within the atom, they fall back, as it were, to the lower level, radiating the energy thus set free as light. This idea has been developed by Bohr himself, Sommerfeld and many other physicists into a most comprehensive and detailed theory covering practically the whole of the vast body of the very precise observations concerning light emission comprised in the data of spectroscopy. But the Bohr theory of electron orbits and their "jumps" throws very little light upon the atomic nucleus. In fact, it is found that not only the optical, but all other ordinary physical and chemical properties of the atom are determined almost entirely by the number and size of the outermost electron orbits. Only the total number of electrons external to the nucleus is fixed by the place of the atom in the scheme of chemical classification or periodic table, and this connection is confirmed and made exact by the remarkable correlation discovered by Moseley in the fundamental frequencies of the very short waves termed X-rays emitted by the atom with its place in the periodic table (atomic number). The Bohr theory applied to Moseley's empirical law shows that the nucleus of an atom has a positive charge which is invariably an exact integral multiple of the charge on an electron, and this integer is identical with the atomic number, varying thus from 1 for hydrogen to 92 for uranium. If it be assumed that the positive electricity in the nuclei is composed of units each equal to the electronic charge, and each identical with the hydrogen nucleus—or proton—then the number of protons and electrons in the nucleus is immediately deducible from the atomic weight and the atomic number of the atom in question, for the weight of an electron is practically nothing—one-eighteen-hundredth, roughly, of the weight of the proton.

Thus the helium atom, weighing almost exactly four times as much as a hydrogen atom, and having an excess positive charge of two units, must contain four protons (to make up the weight), and two electrons as well (to bring its positive charge down from four to two).

The nucleus theory of atom-structure was immediately invoked to explain the difference between the disintegration of radium and other radio-active atoms and ordinary chemical changes. The vastly greater amounts of energy associated with radio-active transformations and the entire independence of these with respect to changes of temperature, pressure, and state of chemical combination had from a much earlier date made it obvious that the process of radio-active transformation was one entirely different from ordinary chemical change, and it now became clear that, whereas in the latter only the outermost peripheral electrons were involved, in the former a disruption of the nucleus took place. The relatively enormous energy of radio-active change—reckoned, of course, per atom disrupted, was the natural consequence of the strength of the forces binding together the component nuclear particles.

Hence it appeared highly probable, if not certain, that to effect artificial disintegration of stable kinds of atoms, the agent employed must possess intrinsic energy of the same order as that released by radio-active disintegration. The only existing agencies satisfying this condition twenty years ago were these very radiations emitted by radium and its radio-active fellows, *viz.*, the α-rays identical with swift moving helium particles ; β-rays, or electrons with speeds approaching closely the velocity of light ; and the extremely short-wave form of light known as γ-rays. The artificial production of any of these called for voltages of the order of a million volts at least, and, at that date no apparatus, except perhaps the Tesla transformer, had been devised which could generate current at this enormous voltage.

Professor Ramsay, of University College, London, published in 1908, an account of experiments in which he claimed to have produced minute traces of lithium by the action of α-rays on a solution of copper sulphate. Other experimenters bombarded uranium oxide with high-speed electrons (cathode rays or β-rays), or with intense γ radiation. Ramsay's claims failed to find confirmation when his experiments were repeated by other workers, and the results of other experiments were likewise negative or unsubstantiated. But in 1919 Rutherford, following up an observation made by Marsden on the production by α-ray bombardment of a corpuscular type of ray of extremely long range, obtained indisputable proof of the power of α-rays to disintegrate atoms of nitrogen on which they impinged.

Other kinds of atoms—boron, fluorine, sodium, aluminium, phosphorus, for example—proved similarly vulnerable; negative results were at first obtained with beryllium, carbon, neon, magnesium, and silicon. The list of disintegrable atoms was further extended in a series of experiments carried out by Rutherford in conjunction with Chadwick. The technique of these experiments is simple. α-rays from a powerful source, such as radium or polonium, are allowed to impinge directly on a layer of the substance to be tested, so thin that it is penetrated by the majority of the rays, which travel only an inch or two further through the air. If, now, a zinc sulphide screen, *i.e.*, a thin translucent layer of this compound deposited on a glass slip, is placed just beyond the range of these α-rays, no scintillations are observed upon it unless the α-rays cause disintegration of some of the atoms through which they pass, giving rise to emission of a corpuscle with a range exceeding that of the α-rays themselves. Such long-range particles were observed from the elements enumerated above, and Rutherford was able to show that these ejected particles were, in all cases, hydrogen nuclei (protons) moving at speeds so high that in some cases their energy far exceeded that of the α-rays which caused their ejection from the impacted nucleus. This fact alone made it certain that the secondary particles could not be merely the nuclei of hydrogen atoms contained perhaps as an impurity in the substance bombarded. The attractive possibility of finding a new source of power in this way is, however, somewhat heavily discounted by the fact that not more than one α-ray in ten thousand makes a direct encounter with the nucleus of any of the thousands of atoms through which it passes, and that not all of those which do make nuclear impact bring about disintegration.

The scintillation method of observation, though simple and well suited for preliminary survey, can give only average results, and affords little information concerning the detail of the nuclear change occurring at and after impact with the α-ray. Far more information is obtained by the use of the Wilson cloud chamber, by means of which the track of the α-ray and, if nuclear impact and distinction occur, of the ejected proton also, are made visible or can be photographed. These photographs show that in general the α-ray is retained by the disrupted nucleus converting it after the loss of the proton into an atom, the atomic number—or nuclear charge—of which, is higher by one unit (2 −1), and the atomic weight by three (4 −1). Thus the nuclear reaction in the case of nitrogen, for example, is expressible by a simple equation of chemical type:

$$ {}_7N_{14} + {}_2He_4 = {}_8O_{17} + {}_1H_1. $$

In this equation the subscript numeral preceding the chemical symbol for the atom denotes the nuclear charge—which determines the atomic number or chemical species—that following it, the atomic weight.

It will be observed that it is necessary to assume the existence of an oxygen atom of weight 17.

In view of the knowledge that the majority of elements have different isotopic or chemically identical kinds of atom of the same atomic number but different atomic weight, such an assumption presents no difficulty and, in fact, the actual existence of oxygen atoms of atomic weight 17 and 18, mixed in small proportions with those of weight 16, has since been established by spectroscopic analysis of the light from oxygen.

During the ten or twelve years following Rutherford's first success, experimental work in this field consisted mainly in repetitions with unimportant variations of his experiments. No vital advance, either in technique or results, was made. Then, suddenly, only two years ago two fresh lines of attack developed.

The first originated in experiments carried out in the German National Physical Laboratory (Reichsanstalt) at Berlin, by the Director, Dr. Bothe, and an assistant, Dr. Franz, to test the possibility of producing γ-rays by bombarding metals with α-rays in place of the electron stream used in X-ray tubes for this purpose. Radiations of a penetrating power as great, or even exceeding that of the γ-rays, were found to be emitted from many of the lighter elements, including lithium, boron, and beryllium, those from beryllium being both more intense and more penetrating than from any other element tested. Repeating these experiments, Professor Joliot of the Radium Institute in Paris, and his wife—a daughter of Madame Curie—found that these secondary rays from beryllium possessed a remarkable power of ejecting hydrogen nuclei at exceedingly high speeds from hydrogen-containing substances, such as paraffin. Believing, as Bothe did, that the rays were, like X-rays and γ-rays, high frequency waves of light, they were disposed to explain this effect on lines similar to those on which Arthur Compton of Chicago, a few years ago, had explained the ejection of electrons from atoms by X-rays. But the energy of the ejected protons which have nearly 2,000 times the mass of an electron is so great that an almost impossibly high quantum value would have to be assigned to the beryllium rays. It was Dr. Chadwick, Assistant Director of the Cavendish Laboratory, who seized upon this difficulty of interpretation and proposed a bold alternative, namely that the rays generated by the impact of α-rays upon the nuclei of beryllium atoms are not waves at all, but an entirely new kind of sub-atomic particle.

Chadwick, from calculations made upon the estimated energy of the protons ejected from paraffin by these rays, was able to show plausibly that they themselves possessed an effective mass approximately equal to that of the hydrogen atom. Yet they could not be protons, for they did not appreciably ionise a gas through which they pass, as protons invariably do. Nor did they carry either positive or negative charge, for they suffered no deflection under the action of the most powerful magnetic forces. If corpuscular in type, they must therefore be, like normal hydrogen atoms, electrically neutral. But it is quite impossible to conceive of particles of the type and structure of normal unchanged atoms, even the smallest of them, penetrating a hundred feet or more of air, or several inches of lead. Here, then, is a pretty enigma. The solution, said Chadwick, lies in the existence of a particle consisting of a combination of proton and electron in a union far more intimate than they share in the hydrogen atom. Such particles would not only be electrically neutral—for the changes of proton and electron are equal and opposite—but would have no external electric field, and would therefore cause no disturbance to an atom through which they pass, unless they impinge upon its nucleus. Losing no energy, they would penetrate far through matter. Such particles, termed "neutrons", had been postulated by various previous writers, notably by Orme Masson in the scheme of atomic constitution which he propounded in 1921, still earlier by W. H. Bragg, as a suggested explanation of the penetrating powers of X-rays—before the proof that these were merely very short light waves was given by Laue's experiment—and by Rutherford, who made Glasson search for them in vain.

Chadwick's suggestion has met with general acceptance although certain disagreements respecting the precise mass of the neutrons have arisen between the various experimenters who have attempted to estimate it.

It is well to remember, too, that the distinction between a wave-disturbance of extremely high frequency and a corpuscle of extremely small dimensions travelling at a speed approaching the velocity of light, is by no means easy to make. Not only does a wave-train appear to possess the properties of localised mass, momentum, and energy which characterises a moving particle but, even more paradoxically, the minute particle may, under certain circumstances, behave as does a train of waves, exhibiting the effects of diffraction and interference which have until recently been ascribed exclusively and distinctively to waves. These propositions, which are based on very definite experimental results, form the foundation of the new theory called "wave-mechanics". Whether ultra-high frequency wave-train or neutral particle, the neutron is admirably adapted as an agent of attack on the nucleus for, carrying no electric charge, it passes unimpeded through the outer screen of electrons, and is neither diverted nor repelled as are protons or α-rays by the nuclear charge itself. In fact, the neutron has already proved itself a most potent disintegrating agent. But before reporting the detailed evidence of its powers, I wish to give a brief account of the second of the two lines of attack mentioned above.

It has already been mentioned that bombardment by high speed electrons had been found by the early experimenters to be entirely ineffective in causing nuclear change. Messrs. Cockcroft and Walton at the Cavendish Laboratory accordingly decided to try the effect with artificially accelerated particles carrying positive charges, and chose for their first attempt the simplest of these, *viz.*, the hydrogen nucleus or proton. Applying voltages of six hundred thousand volts to these in a vacuum tube some eight feet in length, they directed the stream upon a fragment of lithium metal. Immediately particles of far higher energy than the bombarding protons were found to emerge from the lithium. From their range and the ionisation they produced these were identified as α-particles. It appears practically certain that these α-particles are formed by the co-option of the proton in the lithium nucleus and subsequent disintegration of this according to the equation :

$$_3Li_7 + _1H_1 = 2_2He_4.$$

These first results have been confirmed and extended to other elements than lithium by several other experimenters, and the surprising fact has come to light that voltages as low as 30,000 volts, a value far below that employed on long distance transmission lines, are effective in causing disintegration. There would seem to be a distinct possibility, therefore, that weighable quantities of elements could be transmuted even today by means of intense proton bombardment of the lighter elements. But, quite recently, an atomic missile of greater potency has been discovered in the nucleus of an isotopic form of hydrogen—in America yclept " deuterium ", in England " diplogen "—which has a weight almost exactly twice that of the proton but, like it, carries a but single positive charge. In California and, subsequently, in England, it has been found that the nuclei of this atom, impelled to high speed in vacuum tubes by high voltage, are exceedingly efficient in causing disintegration of light atoms on which they impinge and are themselves very readily disintegrated by such bombardment. Protons, α-rays and neutrons result from those disintegrations of various kinds of the lighter atoms, the latter in numbers far exceeding anything that could be hoped for by using the most intense α-rays. In all these artificially produced disintegrations the efficiency of the bombarding particle in causing disruption of the nucleus on which it impinges increases rapidly with its speed above a certain lower limit below which it has no effect at all. For this reason, in all large research laboratories where experiments of this kind are going on, strenuous efforts are being made to develop electrical generators which will impel charged ions, such as protons or diplons to speeds corresponding to a driving force exceeding a million volts.

In the U.S.A., Princeton University, in conjunction with the Massachusetts Institute of Technology, have constructed a gigantic electrostatic generator which, ultimately, is expected to furnish a current of several micro-amperes at upwards of ten million volts.

Incidentally, it may be remarked that it is one problem to obtain these high voltages, another to find a form of vacuum tube to which they can be applied. For this reason various methods have been devised whereby an impulse of relatively low voltage can be repeatedly applied to the same particle. Professor Lawrence, of the University of California, ingeniously effects this by bending the path of the charged particles into a circle by means of a magnetic field and has, in this way, using only 100,000 volts, obtained speeds equivalent to the application of 3,000,000.

Professor J. W. Beams, of the University of Virginia, uses a long straight vacuum tube containing a series of electrodes within it, so spaced that as they pass through these the particles receive at each electrode the impulse due to a travelling wave of high voltage sent along an artificial transmission line connected at chosen points to the electrodes.

By such devices charged atoms or ions, such as the nuclei of hydrogen or of diplogen, can be impelled, *in vacuo*, to such speeds that they experience but slight impediment or loss of energy in passing through matter except when they encounter an atomic nucleus and, in this case, if the encounter be sufficiently direct, they will enter the nucleus, and may thus cause a change in the nuclear system with or without a disruptive cataclysm, but in any case resulting in the formation of a different kind of atom.

From a commercial point of view the scale of magnitude of the transmutation hitherto effected by such means must be regarded as trivial. Lawrence and Livingstone state that they have obtained a yield of ten million neutrons per second by bombarding beryllium with a "deuton" current of three hundred-millionths of an ampere at three million volts, at which rate of production it would take more than 200 million years to transmute one gramme of beryllium. Yet even at this rate the intensity of neutron radiation is comparable with that of X-rays from early types of X-ray bulb, and plans are now being prepared for the construction of apparatus to increase this yield a thousand fold. For this purpose the present apparatus, described briefly above, will be greatly enlarged in size, the magnet employed for bending the "deutons" into circular paths will weigh eighty-five tons, and increased in power so that the present limit of speed corresponding to an accelerating voltage of five million volts will be increased to twenty million.

To what end this enormous expense and trouble? Is it anticipated that neutrons can be used in place of X-rays for the irradiation of malignant tumours?

That is unlikely, though not perhaps incredible. But a far more interesting possibility is already in view, namely, the artificial production of radio-active substances.

The honour of making the important discovery that new types of radio-active atoms can be obtained by transmutation belongs to Professor Joliot and his wife. Bombarding such light elements as aluminium, boron, and magnesium with α-rays, they were able to detect a delayed emission of highly energetic corpuscles from the bombarded matter, subsequent to the cessation of the α-ray bombardment.

This could mean nothing else than that the atoms formed by transmutation were of a kind which, like radium disintegrated, after a more or less brief existence, with emission of a corpuscle. The actual particles emitted, however, were proved to be not the familiar β-rays or electrons, but particles of opposite sign through identical mass, in fact, the positive electrons or "positrons", which were first brought to light only two years ago in the experiments of Dr. Carl Anderson of Pasadena, on the effect of cosmic rays in ejecting corpuscles from matter through which these rays pass. The average life of these new kinds of radio-active atoms was two and a half minutes for the shortest, fourteen minutes for the longest lived. The Joliots write the equation of transmutation of boron and that for subsequent disintegration of the radio-active atom—an unstable isotope of nitrogen—produced as follows:

$${}_5B_{18}+{}_2He_4={}_7N_{13}+{}_0n_1$$
$${}_7N_{13}={}_6C_{13}+e^+.$$

They also pointed out that if this view of the process were correct, it should be possible to produce the radio-active nitrogen by proton bombardment of carbon, thus:

$${}_6C_{12}+{}_1H_1={}_7N_{13}.$$

Cockcroft and Walton thereupon tested this suggestion with their 600,000 volt apparatus at the Cavendish Laboratory, with immediate success.

The chemical identity of the new atom with nitrogen has been proved by chemical tests; its "half-life" in each case was found to be ten and a half minutes, which would make it, weight for weight, some hundred million times as " active " as radium.

Still more recently Professor Fermi of Rome has shown that, as might be expected, irradiation by neutrons is an extremely powerful method of producing new kinds of radio-active elements.

In his first report on his experiments published last May, he could already speak of no less than twenty-three new sorts of radio-active atoms produced in this way, with half-lives ranging from ten seconds to two days; in a later report (June 16) this number is increased to more than forty. He describes similar experiments made upon the heavy elements thorium and uranium, with production in the latter case of an element of atomic weight 93*, *i.e.*, higher than that of uranium—the highest hitherto known. Apparently, therefore, neutron bombardment of atoms is competent to bring about transmutation of the heaviest known nuclei, the large positive charges of which enable them to repel protons, deutons and α-rays. It is with the object of obtaining copious streams of neutrons for such transmutations that Lawrence and his collaborators at the University of California are building the gigantic apparatus to which reference has already been made. Should their experiments prove the feasibility of thus producing radio-active elements, even at the rate of a millionth of a gramme per hour, it is clear that a prospect will be disclosed of supplementing the meagre and very costly natural supply of radium, with consequences of great medical value and, perhaps, of wider economic interest.

* This identification now appears doubtful.

It is regretted that it has been found necessary to raise the price of ENVIRONMENT to sixpence per copy; but it has so far been produced at a loss, and it was a matter of ceasing publication, or of raising the cost to the purchaser to the still low price at which it now appears.

Subscribers who have already paid the subscription for Volume II will not be asked to increase their subscription for that volume.