The New Hydrogen*

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FOR more than a century scientific men believed with confidence that pure water was a well-defined chemical substance, H_2O, of molecular weight 18. This belief was shown by the fact that the unit of mass, the kilogram, consisting of a cylinder of platinum-iridium, was initially chosen to be of the same mass as 1,000 cubic centimetres of water at the temperature of maximum density. Subsequent measurements showed that this was slightly in error, so that the unit of mass was defined in terms of the metal standard. It was only about four years ago that this confidence was slightly disturbed as a result of the study of the isotopic constitution of oxygen. Instead of being a simple element of mass 16, oxygen was found to contain in small quantity isotopes of masses 17 and 18. It was clear from this that pure water must contain some molecules of weight 19 and 20 as well as the normal 18. Since, however, it seemed very unlikely that the proportion of the isotopes could be sensibly changed in the processes of preparation of pure water, this result, while of much theoretical interest, did not appear to have any practical importance.

As a result of investigations during the last two years, there has been a revolutionary change in our ideas of the constancy of the constitution of water. This has resulted from the discovery that a hydrogen isotope of twice the normal mass is always present in preparations of ordinary hydrogen. While this isotope of mass 2 exists only in small proportion—only about 1 in 6,000 of the main isotope of mass 1—yet, on account of the marked difference in mass of the two components, the relative concentration of the two isotopes can be varied in a marked way by various physical and chemical processes. This is seen by the fact that we are now able to obtain preparations of water in which the isotope of hydrogen of mass 1 is completely replaced by the isotope of mass 2. The density of the heavy water is about ten per cent greater than ordinary water; while its freezing point is 3·8° C., and its boiling point 1·42° C., higher. Though in outward appearance this heavy water resembles ordinary water, yet in general its physical and chemical properties show marked differences. Not only does the vapour pressure vary markedly from the normal, but also the latent heat is considerably higher. Both the surface tension and specific inductive capacity are lower while the viscosity is much greater.

It is of interest to indicate briefly the almost romantic history of this rapid advance in knowledge, and to note that there are certain points of analogy between the discovery of heavy hydrogen and the discovery of argon in the atmosphere by the late Lord Rayleigh. In both cases the clue to the discovery depended on the recognition of the importance of small differences observed in accurate measurements of density.

When the relative abundance of the isotopes of oxygen was first measured, Birge and Mendel showed that there was a slight discrepancy—only about 1 in 5,000—between the ratio of the masses of the atoms of hydrogen and oxygen measured by Aston by the method of positive rays and the ratio deduced by direct chemical methods. They concluded that this small difference was greater than the probable experimental error in the measurements and in explanation suggested that hydrogen might contain in small quantity—about 1 in 4,000—an isotope of mass 2. Let us consider for a moment how the presence of such an isotope could be demonstrated by direct experiment. Both the H^1 and H^2 isotopes would have the same nuclear charge of 1, and have one external electron, and would thus be expected to give the same type of optical spectrum under the influence of the electric discharge. It is to be remembered, however, that the electron, the movements of which when disturbed give rise to its characteristic radiations, is coupled to the nucleus; and that the rates of vibration, although mainly governed by the nuclear charge, are slightly affected by the mass of the nucleus itself. On account of the greater mass of the H^2 isotope, it can readily be calculated that the Balmer lines in the spectrum of heavy hydrogen should appear slightly displaced towards the red. In the case of the α line, the displacement amounts to 1·78 angstrom units. When an electric discharge is passed through ordinary hydrogen, weak satellites should thus appear on the side towards the red. The presence of such weak satellites in the right position was first detected in experiments made for the purpose by Urey, Brickwedde and Murphy. The intensity of the satellite compared with the strong H_α line was difficult to measure with certainty but was found to be of the order of 1 to 5,000.

Experiments were then made to enrich the H^2 isotope by fractional distillation of liquid hydrogen; and with some success. Another important observation was made by Urey and Washbourn, who found that the water in old electrolytic cells contained a larger proportion of heavy hydrogen than the normal. The concentration of H^2 was found to be rapidly enriched by continued electrolysis. This gave the key to a successful method of obtaining heavy hydrogen in quantity. The processes involved were carefully investigated by Lewis and Macdonald, and the electrolysis of water was carried out on a comparatively large scale. Nickel electrodes were used, and sodium hydroxide as an electrolyte. In general, it was found that the escape of H^1 during electrolysis was five to six times faster than that of H^2 relative to their

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concentrations in the solution. There was in consequence a steady accumulation of the heavy isotope in the water in the process until nearly pure heavy water was obtained. Assuming that the initial concentration of H^2 in the water was 1 in 6,000, about 1 c.c. of pure heavy water should be obtained by electrolysis of 6 litres of water.

Lewis succeeded in preparing many cubic centimetres of heavy water in which ordinary hydrogen was present in very small quantity. He and his collaborators investigated the main physical and chemical differences between heavy water and ordinary water, to some of which I have already referred. Our congratulations are due to our American colleagues for the masterly way they have opened up and developed so rapidly this new field of knowledge, which it is certain will prove of great scientific and practical importance in many directions in the near future. Prof. G. N. Lewis, of the University of California, who was the first to prepare nearly pure heavy water, generously presented samples of this water to a number of investigators, not only in his own country but also in Europe, in order to give them an early opportunity of testing its properties. I am personally much indebted to Prof. Lewis for a sample of this heavy water with which we were able to make a number of experiments on the transformation of matter to which I shall refer later.

We are all aware of the important part that hydrogen plays in many chemical compounds and particularly in organic molecules. When reasonable supplies of heavy water are available to the experimenter, there will no doubt be great activity in preparing and studying many compounds in which H^1 in the molecule is wholly or partly replaced by H^2. Already a few investigations have been carried out, for example, with ammonia and with hydrogen iodide, in which H^1 is replaced by the heavy isotope. It has been found that in mixtures of light and heavy hydrogen gas, the atoms interchange on a nickel surface at a temperature of about 600° C. and the conditions of equilibrium and heat evolution have been investigated. During the next few years we may expect an intensive study to be made of the change of properties of compounds in which heavy hydrogen is used. It will be of particular interest to examine the changes in the rates of reaction at different temperatures when heavy hydrogen is substituted for ordinary hydrogen.

The discovery of the new water will be of great importance in another direction, namely, its effect on the processes occurring in animal and plant life. There has not yet been sufficient time to make more than a few preliminary experiments in this field, and then only on a small scale. Lewis finds that seeds of a certain tobacco plant did not germinate in pure heavy water but did so when the concentration of heavy hydrogen was about one half. In experiments by other observers, well-defined physiological effects have been obtained for quite small concentrations of heavy hydrogen in water. Further observations in this highly important field of inquiry will be awaited with much interest.

It is widely recognised that the new hydrogen will prove of so much general importance to chemistry and physics that it is desirable to give it a definite name and symbol. Prof. Urey, its discoverer, has suggested that the isotope of mass 1 should be called 'protium' and the isotope of mass 2 'deuterium'; while the nucleus of heavy hydrogen, which has already been found very efficient as a projectile in transforming matter, should be called 'deuteron' or 'deuton'. The question of a suitable nomenclature is one of general importance to scientific men and deserves careful consideration. The name 'diplogen' (διπλους, double) for H^2 and 'diplon' for the nucleus seemed to find some favour in England as an alternative. The symbol D for the heavy isotope seems appropriate.

While diplogen (or deuterium) may be separated in quantity from heavy water in nearly a pure state, it is of interest to refer to another method of separation employed by Hertz. By utilising a special diffusion method devised by him, he has been able to separate from ordinary hydrogen gas about 1 c.c. of diplogen in such purity that the Balmer lines of hydrogen were not visible in its spectrum. With such pure material, it should be possible to study in detail the complicated band spectrum of diplogen and compare it with that of hydrogen.

We have not so far considered the question of the nuclear structure of diplogen and its relation, if any, to that of ordinary hydrogen. We first of all require to know its mass with accuracy; this has been measured by Bainbridge by using a modification of the positive ray method, who found that the mass of the atom is 2·0136 while the mass of the hydrogen atom is 1·0078 in terms of the mass of the main isotope of oxygen taken as 16. This mass is slightly less than the combined mass of two H atoms. Sufficient evidence is not yet available to decide whether the D nucleus is simple or composite, and there are a number of possible combinations to consider between the four units, the electron, positron, neutron and proton. If we assume, as seems not unlikely, that the D nucleus consists of a close combination of a proton with a neutron, it can be shown from the masses concerned that its binding energy should be somewhat less than 1 million volts if we take the value 1·0067 for the mass of the neutron as estimated by Chadwick. If this be the case, we should expect the diplon to be broken up occasionally into a proton and neutron as a consequence of a close collision with a fast α-particle. Experiments to test this have so far yielded negative results. If this dissociation occurs at all, the probability of such an event must be very small. Lawrence, from a study of the bombardment of elements by diplons, suggests that the diplon may break up into a proton and neutron in the strong electric field close to the bombarded nucleus, but the interpretation of his results is not yet certain. At the moment, therefore, the experimental evidence is insufficient to give a definite decision with regard to the structure of the diplon.

By comparing the scattering of α-particles when passing through diplogen and hydrogen gas, Mr. Kempton and I have found that as the result of a head-on collision with an α-particle, the recoiling diplon travels about eight per cent farther than the proton in a corresponding collision. Such a result is in agreement with calculation. It also seems clear that the field of force round the diplon must be very similar to that of the proton, although it may be expected that some differences would be shown for very fast α-particles if the diplon is composite as we have supposed.

TRANSMUTATION OF ELEMENTS

The discovery of heavy hydrogen has provided us with a new form of projectile which has proved markedly efficient in disintegrating a number of light elements in novel ways. It was a very fortunate coincidence that, when Prof. Lewis had prepared some concentrated diplogen, his colleague in the same University, Prof. Lawrence, had available his ingenious apparatus for producing high-speed protons and other particles with an energy as high as two million volts. When diplogen was substituted for hydrogen, the diplon (D^+) was found to be about ten times as efficient in promoting some transformations in lithium as H^+ of equal energy. It will be remembered that Cockcroft and Walton found two years ago that lithium, when bombarded with fast protons, was transformed, with the emission of swift α-particles. It seems clear that in this case the lithium isotope of mass 7 is involved. A proton is captured by the nucleus and the resulting nucleus breaks up into two α-particles, ejected in nearly opposite directions, according to the relation

$$Li_3^7 + H_1^1 \rightarrow He_2^4 + He_2^4$$

The emission of other particles of short range has also been observed but the exact nature of the transformation which gives rise to them is not yet clear.

When lithium is bombarded with diplons instead of protons, different types of transformation occur. In one case it seems that the lithium isotope of mass 6, after capturing a diplon, breaks up into two α-particles according to the equation

$$Li_3^6 + D_1^2 \rightarrow He_2^4 + He_2^4$$

In this case also, as has been shown beautifully by the expansion photographs obtained by Dee and Walton, the two α-particles are shot out in opposite directions and with a speed greater than the swiftest α-particle from radioactive substances.

Still another interesting type of complex transformation occurs in this element. Oliphant and Rutherford observed that lithium when bombarded by diplons gave, in addition to the group of fast α-particles first observed by Lawrence, a distribution of α-particles of all ranges from 7·8 cm. to 1 cm. in air. It is believed in this case that the isotope of mass 7 captures a diplon and then breaks up into two α-particles and a neutron according to the relation

$$Li_3^7 + D_1^2 \rightarrow He_2^4 + He_2^4 + n_0^1$$

This transformation is in close accord with the conservation of energy when the change of mass and the energies of the expelled particles are taken into account. The emission of neutrons from lithium has been observed by Lauritsen and also in our experiments. In addition, Lawrence has shown that a number of other light elements give rise under bombardment to groups of fast protons and in many cases also to α-particles and neutrons. While the interpretation of the experimental results is as yet only clear in a few cases, there can be no doubt that the use of heavy hydrogen will prove invaluable for extending our knowledge of transformations and thus in helping to throw light on the structure of atomic nuclei.

The importance of this new projectile in studying transformations is well illustrated by some recent experiments made in Cambridge with Oliphant and Harteck. When diplons were used to bombard compounds like ammonium chloride, NH_4Cl, and ammonium sulphate, $(NH_4)_2SO_4$, in which ordinary hydrogen was in part displaced by diplogen, enormous numbers of fast protons were found to be emitted, even for an accelerating voltage of 100,000 volts. In fact the number of expelled particles is far greater than that observed in any other type of transformation at this voltage. The main groups of expelled protons had a range in air of 14 cm., corresponding to an energy of 3 million volts. In addition to this group, another strong group of singly charged particles were observed of range in air only 1·6 cm. Both of these groups contain equal numbers of particles.

In order to account for these observations, it seems likely that, as the result of a close collision, the diplon occasionally unites with the struck diplon to form a helium nucleus of mass 4 and charge 2, but containing a large excess of energy over the normal helium nucleus. The new nucleus is in consequence explosive and breaks up into two parts, one a fast proton and the other a new isotope of hydrogen H_1^3 of mass 3. If this be the case, the proton and H^3 nucleus should fly apart in opposite directions. It can be simply calculated that the range of the recoiling H^3 nucleus under these conditions should be 1·7 cm.—a range agreeing closely with that actually observed. The changes occurring are illustrated by the equation

$$D_1^2 + D_1^2 \rightarrow He_2^4 \rightarrow H_1^3 + H_1^1$$

From the known masses of D and H^1 and the energy of the observed motion of the H^1 and H^3 particles, it can be deduced that the mass of this new hydrogen isotope is 3·0151.

In these experiments, large numbers of neutrons are also emitted. It appears probable that these arise from another mode of disintegration of the newly formed helium nucleus according to the relation

$$D_1^2 + D_1^2 \rightarrow He_2^4 \rightarrow . He_2^3 + \text{neutron},$$

an isotope of helium of mass 3 and a neutron being expelled in opposite directions. There is strong evidence that such an isotope of helium also appears when the lithium atom of mass 6 is bombarded by protons, and from this transformation it appears that the mass of this isotope is 3·0165. It is quite likely that the helium nucleus of mass 3 formed in this way is unstable and may possibly break up into H_1^3 and a positive electron. While the conclusions outlined above are to some extent provisional and require confirmation by other methods, there can be no doubt that the effects which follow the collisions of a swift diplon with another are of much importance and interest in throwing light on possible modes of formation of some of the lighter nuclei.

It is of interest to speculate why the heavy isotope of hydrogen appears in many cases far more effective, for equal energies, in producing transformations than the lighter isotope. On the general theory of transformation proposed some years ago by Gamow, it is to be anticipated that, for equal energies of motion, the diplon on account of its heavier mass would have a smaller chance of entering a nucleus than the swifter proton. It may be, however, that normally only a small fraction of the protons which actually enter a nucleus are able to cause a veritable transformation, the others escaping unchanged from the nucleus. On this view, the greater efficiency of the diplon in causing transformation may be due to the fact that a much larger fraction of those which enter the nucleus are retained by it, leading to a violent disintegration of its structure. It may be too that the diplon on entering a nucleus breaks up into its component parts. The appearance of the proton as well as the neutron in some of the transformations may be connected with the composite structure of the diplon.

Deep Water Circulation of the Atlantic

DR. G. WÜST, oceanographer in the German research vessel *Meteor*, has recently published the first part of vol. 6 of the reports of the German Atlantic expedition[*]. The report is not only a description of the *Meteor*'s results, but is also a history of the investigation of the Atlantic deep waters, and gives a critical summary of all the observations that have been made from those of H.M.S. *Challenger* (1873–1876) to those of the R.R.S. *Discovery II* (1929–1931). At the end of the report is a complete list of the observations used.

Dr. Wüst has made extensive use of the principle that if the water in a deep current sinks to a lower level, its temperature will increase as the water becomes adiabatically compressed; and conversely, that if the deep current rises, the water in it is cooled owing to adiabatic expansion. Any attempt to follow the path of a deep current in a vertical section showing temperature distribution is made much more difficult by these changes. It was first suggested by Prof. Helland-Hansen that the difficulty should be removed by using vertical sections showing the distribution of potential temperature—the temperature to which the water would be cooled if it were raised adiabatically to the surface. This report is a striking tribute to the advantage of this method.

In the report there are charts showing the actual temperature, the potential temperature, and the salinity of the bottom water (at depths greater than 4,000 metres) over the whole of the Atlantic Ocean. There are also vertical sections which show the distribution of potential temperature, and salinity, along the east and west Atlantic basins, on either side of the mid-Atlantic ridge. With their help, Wüst shows that the flow of antarctic and arctic bottom waters is much more asymmetrical than it was thought to be. Antarctic bottom water flows northwards along the sea bottom, mixing with the warmer North Atlantic deep water which is flowing southwards above it. The last traces of the antarctic water reach as far as 34° N. in the east Atlantic basin and to 40° N. in the western basin. The influence of bottom water of arctic origin can only be detected north of these latitudes as a very weak current.

From the relations between potential temperature and salinity, Wüst has been able to find the percentage of antarctic water at the bottom in both basins in all latitudes. These percentages are shown by two curves. The decrease of the antarctic water along the western basin is almost regular; it is hastened in about 5° S. where the Para rise obstructs the bottom current. In the eastern basin the northward flow is stopped at the Walfish ridge, which extends transversely from the African coast to the mid-Atlantic ridge. The antarctic bottom water north of this ridge enters the basin from the west through the Romanche channel, a break in the mid-Atlantic ridge near the equator. The bottom water flowing through this channel spreads southwards to the Walfish ridge and northwards to 34° N. By means of a chart showing the distribution of potential temperature at the bottom of the Scotia Sea, based principally on the observations made by the ships of the "Discovery" Committee, Wüst has been able to show that antarctic

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[*] *Schichtung und Zirkulation des Atlantischen Ozeans.* Lief. 1: *Das Bodenwasser und die Gliederung der Atlantischen Tiefsee.* Von Georg Wüst. (Wissenschaftliche Ergebnisse der Deutschen Atlantischen Expedition auf den Forschungs- und Vermessungsschiff *Meteor* 1925–1927, herausgegeben im Auftrage der Notgemeinschaft der Deutschen Wissenschaft von A. Defant, Band 6, Teil 1.) Pp. 107+8 Beilagen. (Berlin und Leipzig: Walter de Gruyter und Co., 1933.) 20 gold marks.