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The New Hydrogen: THE LORD RUTHERFORD OF NELSON ... 21

Obituary:
George Cary Comstock: PROFESSOR JOEL STEBBINS 25

Scientific Events:
International Conference on Physics; Soil Surveys of the Department of Agriculture; The Scientific Exhibit at the Cleveland Meeting of the American Medical Association; Memorial to Sir Walter Fletcher; In Honor of Professor William Herbert Hobbs ... 26

Scientific Notes and News ... 30

Discussion:
The Crisis at Buitenzorg: DR. DAVID FAIRCHILD and DR. THOMAS BARBOUR. *Chemical and Physiological Properties of Kojic Acid:* DR. THEODORE E. FRIEDEMANN. *Seasonal Effect of Lime on Strawberries:* DR. A. H. MEYER. *Spiraling in Trees:* DR. E. C. L. MILLER ... 33

Quotations:
The New Mathematics—A Lecture by Professor Bieberbach ... 35

Scientific Apparatus and Laboratory Methods:
A Photoelectric Apparatus for Turbidity and Light Penetration Measurement: PROFESSOR M. M. ELLIS. *A Low-price Station Indicator:* PROFESSOR G. D. HARRIS ... 37

Special Articles:
Light in Relation to Dormancy and Germination in Lettuce Seed: DR. LEWIS H. FLINT. *The Prevalence of Streptococcus Bacteriophage:* ALICE C. EVANS. *Effects of Protracted Exposure to a Loud Tone:* GLEN FINCH and PROFESSOR ELMER CULLER 38

Science News ... 6

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THE NEW HYDROGEN[1]

By the LORD RUTHERFORD OF NELSON

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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 centimeters 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 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, about 1 in 6,000 of the main isotope of mass 1, yet, on ac-

[1] Lecture before the Royal Institution of Great Britain, March 23, 1934.

count 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 this heavy water is about 10 per cent. greater than ordinary water; while its freezing point is 3.8° C., and its boiling point 1.42° C. higher. While in outward appearance this heavy water resembles ordinary water, yet in general its physical and chemical properties show marked differences. Not only does the vapor pressure vary markedly from the normal, but 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 using 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, whose movements 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 be readily 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 Angström 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 Washburn, 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, who carried out the electrolysis of water on a comparatively large scale. Nickel electrodes were used, with sodium hydroxide as an electrolyte. In general, it was found that the escape of H^1 during electrolysis was from 5 to 6 times faster than that of H^2 relative to their 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 cc of pure heavy water should be obtained by electrolysis of 6 liters of water.

Lewis succeeded in preparing many cubic centimeters of heavy water in which ordinary hydrogen was present in very small quantity, and with 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 will certainly prove of great scientific and practical importance in many directions in the near future. Professor 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 in Europe, in order to give them an early opportunity of testing its properties. I am personally much indebted to him 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, *viz.*, 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 generally recognized 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. Professor 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 favor 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 utilizing a special diffusion method devised by him, he has been able to separate from ordinary hydrogen gas about 1 cc 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, 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 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 8 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 Professor Lewis had prepared some concentrated diplogen, his colleague in the same university, Professor 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 10 times as efficient in promoting some transformations in lithium as H^+ of equal energy. It will be remembered that two years ago Cockroft and Walton[2] found 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

$$Li^7_3 + H^1_1 \rightarrow He^4_2 + He^4_2$$

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 the lithium isotope of mass 6, after capturing a diplon, breaks up into two α-particles according to the equation

$$Li^6_3 + D^2_1 \rightarrow He^4_2 + He^4_2$$

In this case also, as has been shown beautifully by the expansion photographs obtained by Dee and Walton,[3] 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[4] 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 cms 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

$$Li^7_3 + D^2_1 \rightarrow He^4_2 + He^4_2 + n^1_0$$

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 by Oliphant and Harteck.[5] When diplons were used to bombard compounds like ammonium chloride, NH_4Cl, and ammonium sulfate, $(NH_4)_2SO_4$, 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 cms, corresponding to an energy of 3 million volts. In addition to this group, another strong group of singly charged particles of range in air only 1.6 cms was observed. 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^3_1 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

$$D^2_1 + D^2_1 \rightarrow He^4_2 \rightarrow H^3_1 + H^1_1$$

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

$$D^2_1 + D^2_1 \rightarrow He^4_2 \rightarrow He^3_2 + \text{neutron}$$

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

2 *Proc. Roy. Soc. A.* 137: 229, 1932.
3 *Proc. Roy. Soc. A.* 141: 733, 1933.
4 *Proc. Roy. Soc. A.* 141: 722, 1933.
5 *Nature* 133: 413, 1934.

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 is 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.

In this address I have endeavored to give in a simple way an account of our knowledge of heavy hydrogen which has been gained in the past year and to indicate the great importance of this discovery to science. This new hydrogen will undoubtedly prove of great value in many ways to physics and chemistry and probably also to the biological sciences. There are already indications that much interesting information may be obtained by the application of this new substance to the study of processes in animal and plant life.

In the course of the lecture, experiments were shown to illustrate the differences in freezing point and in vapor pressure between ordinary and heavy water, and the differences in heat conductivity between ordinary and heavy hydrogen. For the first time experiments were made to show the artificial transformation of lithium by protons and diplons of energy corresponding to about 100,000 volts. The enormous emission of fast protons when ammonium sulfate containing heavy hydrogen was bombarded by diplons was clearly shown by counting methods. The transformation apparatus was designed and operated by Dr. Oliphant, while Messrs. Watson and Sons loaned an installation to provide a steady potential of 100,000 volts to accelerate the ions.

OBITUARY

GEORGE CARY COMSTOCK

WHEN a man maintains his strength and his faculties unimpaired up to the age of nearly fourscore, and then is taken suddenly with no long drawn-out illness, we feel that his life was arranged about right. George Cary Comstock was born in Madison, Wisconsin, on February 12, 1855, and died in the city of his birth on May 11, 1934. Thus closed a career which for long was associated with the old-time "astronomy of precision."

Comstock spent his youth and prepared for college in the state of Michigan. Entering the university at Ann Arbor, he took a scientific course and was graduated in 1877. While at Michigan he came under the tutelage of Professor James Craig Watson, who was to influence his whole later life. It was in 1854 that the German astronomer Francis Brünnow was called to Michigan. Trained in the traditions of his home institutions Brünnow carried to a mid-western college the methods of a German university, and lectured in broken English to diminishing classes until Watson was his only student. Yet there were developed by Watson, who ultimately succeeded Brünnow, and the others at Michigan perhaps half of the trained astronomers of America during the seventies and eighties, and one of the foremost of the group was Comstock. After several years as a civil engineer it was in 1881 that Comstock followed Watson to Wisconsin to be assistant in the Washburn Observatory. Then, after Watson's premature death, Comstock served at Madison under Edward S. Holden, later the first director of the Lick Observatory. As a career in astronomy involved considerable uncertainty, Comstock devoted his spare time to the study of law; he was graduated from the Wisconsin law school in 1883, but he never practiced. Nevertheless, he later often referred to his legal training as possibly the most valuable part of his education.

At the age of thirty he was definitely committed to an academic career by an opening at Ohio State University, where he served as professor of mathematics for two years. In 1887 when Holden left to take up active service at the Lick Observatory it was President T. C. Chamberlin who called Comstock to take charge of the Washburn Observatory. Watson and Holden had already given it a place of distinction