Production and Properties of High-frequency Radiation.[1]

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IN my address last year I referred to recent advances in the production of very high voltages for technical purposes, and the application of these voltages to highly exhausted tubes in order to obtain a copious supply of high-speed electrons and atoms and high-frequency radiation. It is of interest to note how rapidly in recent years our ideas have widened as to the possibilities of production of very high-frequency radiation of the X-ray type, both by artificial and natural processes.

On the quantum theory, the energy associated with a quantum of radiation of frequency ν is given by $h\nu$, where h is the well-known constant of Planck. When swift electrons impinge on matter, radiation of an X-ray type is generated over a wide range of frequencies, and it has been verified experimentally that the maximum frequency of the radiation obtainable in this way is limited by the relation $E = h\nu$, where E is the energy of motion of the electron, a result in accordance with energy considerations.

For purposes of discussion, it is very convenient to express the energy of a quantum not in ergs but in terms of a potential difference in volts, through which an electron must fall to acquire an equal energy. Expressed in this way, the energy of a quantum of green light corresponds to 2 electron-volts, or 2 volts for brevity. Before the advent of X-rays the highest frequencies examined were confined to the ultra-violet part of the light spectrum, corresponding to less than 10 volts. Following the discovery of X-rays and the application of methods for determining their frequency, we have been enabled to study radiations over a wide range of individual energy, varying from a few hundred volts to 300,000 volts or more. By the use of special gratings and other methods, the gap in frequency between ordinary ultra-violet light and soft X-rays has been bridged in the last few years. There appears to be no limit to the maximum frequency that can be obtained by the bombardment of matter with electrons, except the practical difficulty of obtaining streams of the requisite high-velocity electrons. In some recent experiments in the Institute of Technology, Pasadena, about 1 million volts has been successfully applied for a short time to a suitably designed X-ray tube. It is stated that the X-rays obtained were of such intensity and penetrating power that they could easily be observed by the luminosity on a phosphorescent screen 100 feet away.

So far our experiments in this direction have been limited to about 1 million volts, and we have not yet been able to produce X-rays in the laboratory of penetrating power equal to that shown by the γ-rays spontaneously emitted by radioactive bodies. The highest frequency observed in their transformations corresponds to between 3 and 4 million volts. Some recent experiments indicate that the γ-rays which accompany the weak radioactivity of potassium are of still greater penetrating power than the rays from radium, but no definite estimate of the maximum frequency has so far been made.

There is in addition another general method of estimating the frequency of radiation that may arise in certain fundamental atomic processes of a simple type. According to modern views, energy and mass are closely connected, and the relation between the energy E resident in a mass m is given by the well-known equation of Einstein, $E = mc^2$, where c is the velocity of light. According to this view, if any system decreases in mass by internal rearrangement, the total energy lost in the process is given by the product of the change of mass multiplied by c^2. If this energy is emitted in the form of a radiation of one definite frequency ν, then $h\nu = c^2 dm$, where dm is the accompanying change of mass of the system. On account of the very small change of mass even for a large emission of energy, it is difficult to give a direct experimental proof of this relation, but there seems to be little doubt of its general validity. Even for the radioactive bodies which in their successive transformations spontaneously emit a very large amount of energy per atom, in the form of α-, β- and γ-rays, the effect to be expected is small and difficult to measure. The atom of uranium of mass about 238, after successive transformations involving the loss of eight α-particles, changes into an isotope of lead of mass about 206. It is to be anticipated that, if the methods of positive ray analysis could be applied to these elements, the difference between the atomic masses of uranium and the resulting lead would include not only the mass of 8 helium nuclei in the free state, but also about 0·05 unit of atomic mass, corresponding to the total emission of energy of about 46 million electron-volts per disintegrating atom of uranium. This difference—about 1 in 4000—should be just detectable by the methods employed by Aston in his study of isotopes. Similarly the change of mass in each transformation can be deduced if the energy released during the process is known experimentally.

We shall now consider the application of these ideas to certain nuclear processes. It is now generally accepted that the nuclei of all the elements are composed of protons (hydrogen nuclei) and electrons. While it is of course difficult to give a definite proof of this hypothesis, we know that it is strongly supported by the work of Aston on the atomic masses of the isotopes of the elements and by the experiments on the liberation of protons from certain light elements when bombarded by swift α-particles. It is generally supposed that the helium nucleus is composed of a close combination of four protons and two electrons. The mass of the helium atom is 4·00216 (O = 16), while the mass of four hydrogen atoms in the free state is $4 \times 1{\cdot}00778$. There is in consequence a loss of

[1] From the presidential address delivered at the anniversary meeting of the Royal Society on Nov. 30.

mass of 0·029 in the formation of the helium atom. This indicates a loss of energy of 27 million electron-volts in the process of building a helium nucleus from free protons and electrons. If it be possible to imagine that in some way this energy is emitted catastrophically, in a single quantum of radiation, the energy of the quantum would correspond to 27 million volts. The energy emitted per atom is thus very large, and it has been suggested by Eddington and others that the formation of helium from hydrogen nuclei and electrons may be one of the sources of the energy radiation from the stars.

In a similar way the total energy emitted during the formation of any atom of known mass from free protons and electrons may be estimated. Since the proton in a free state has a mass 1·0073, and a mass about 1·000 in the average nuclear combination, the energy released per proton is about 7 million volts. For example, the atomic weight of the most abundant isotope of mercury (atomic number 80) is 200·016, and this presumably contains 200 protons, of mass nearly unity, and 120 electrons. Disregarding the small mass due to the electrons, we may conclude that the total energy emitted during the formation of a mercury atom from free protons and electrons is about 1400 million electron volts.

When we consider the extreme complication of such a heavy nucleus and the number of its component parts, it is difficult to believe that this emission of energy can take place in one single catastrophic act. It is so much more likely that the energy is emitted in a step-by-step process during the organisation of the nucleus. Except for light atoms, where the nuclear structure is simple, it is to be expected that the radiation of energy from all complex nuclei would occur in successive stages.

On the other hand, there is one possibility to consider, which was first put forward by Jeans to account for the long lives of the hot stars. He supposes that even the protons and electrons are not indestructible, but may under unknown conditions be transformed into radiation. The total internal energy of the electron is about 500,000 volts, but of the proton 1840 times greater, or about 940 million volts. If we suppose the proton and electron to disappear together in the form of radiation, there must be an enormous liberation of energy. If this energy be emitted in a single quantum, we should expect to obtain a γ-radiation corresponding to about 940 million volts. Such a hypothesis is admittedly of a very speculative nature and may be very difficult of direct proof or disproof.

Apart from the radioactive bodies we have no definite experimental evidence of the emission of penetrating radiations, either in the formation of atoms or destruction of protons, and it may be that the processes considered do not take place under the conditions of our experiments on the earth. On the other hand, the long life of the hot stars indicated by general astronomical evidence does seem to demand some such process or processes in which the liberation of energy is enormous compared with the mass involved.

It is thus of very great interest to examine whether any direct experimental evidence can be obtained of the existence of such extraordinarily energetic γ-rays. This interest is heightened by the experiments in recent years which have shown the existence of an extremely penetrating type of radiation, sometimes called the 'cosmic' rays, in our atmosphere—a radiation much more penetrating than the γ-rays from the radioactive bodies. This radiation has been detected and measured by the small ionisation produced in a closed electroscope. The initial observations were made by Hess and by Kolhörster, and we owe much to the admirable experiments of Millikan and Cameron, who have carefully examined the absorption of this radiation by the water of mountain lakes, which are practically devoid of ordinary radioactive matter.

It is clear from these experiments that the radiation is complex in character, and that there are present radiations which are able to pass through 17 metres of water for a reduction of intensity to one-half value. It is natural to suppose that this radiation is of a γ-ray type, but it should be borne in mind that the effects so far observed would be equally explicable if the radiations consisted not of high-frequency γ-rays, but of high-energy electrons entering our atmosphere.

Assuming, however, that the radiation is of the γ-ray type, it is necessary to consider the factors that determine the absorption of such a radiation by matter. During the past twenty years the problem of the nature of the absorption of X-rays and γ-rays by matter has been the subject of detailed investigations, and there is now a general consensus of opinion of the main features of the processes involved. In the case of the heavier elements, the absorption of ordinary X-rays is mainly due to the interaction between the radiation and the electrons in the atom, whereby the energy of the quantum of radiation is transferred to the electron. This is generally known as the 'photoelectric' effect. In addition, there is a relatively small loss of energy due to the scattering of the incident radiation by the electrons; but in general, except for very high-frequency X-rays and light elements, the absorption due to the photoelectric effect predominates. The case is quite different when we deal with penetrating γ-rays, where the loss of energy due to the process of scattering becomes relatively much more important, and for radiation of the order of 100 million volts almost completely governs the absorption.

The main features of this scattering, known as the Compton effect, are now well understood. There is an occasional interaction between the quantum of radiation and the electron in an atom, whereby the radiation is scattered and the electron set in motion. The scattered radiation is always of lower frequency than the incident radiation, the difference depending on the angle of scattering. In this type of encounter between radiation and an electron, both momentum and energy are conserved, and consequently the energy given to the electron depends on the nature of the encounter and thus on the angle of scattering of the radiation. The essential correctness of this theory has been verified by several distinct methods.

When a pure radiation of definite frequency is passed through matter, there always remains some transmitted radiation which has not been transformed, but mixed with it are degraded radiations of much lower frequency and swift electrons set in motion by the process of scattering. The ionisation observed in a closed vessel is probably mainly due to the electrons liberated by scattering in the medium and the walls of the containing vessel.

Assuming that the laws of the Compton process of scattering are valid for high-frequency radiation, there still remains the difficulty of estimating the probability of such scattering encounters, for on this probability depends the actual magnitude of the absorption coefficient. Different methods of calculating this probability have been given by A. H. Compton, Dirac, and recently by Klein and Nishina. The theory of Compton is based mainly on classical analogies, and that of Dirac on the earlier quantum mechanics. Recently the problem has been attacked again by Klein and Nishina (NATURE, Sept. 15, 1928), using the later relativistic form of wave-mechanics formulated by Dirac. The calculated absorption coefficients for high-frequency radiations differ materially from one another on these three theories, and in particular the theory of Klein and Nishina gives a greater absorption coefficient for a given high-frequency radiation. For radiations of individual energy more than 100 million volts, the coefficient is about five times greater than that given by the formula of Dirac.

Unfortunately, the experimental evidence available from a study of the absorption of the most penetrating γ-rays from radioactive bodies is not complete enough to give a definite test of the validity of these theories. However, Mr. Gray, of the Cavendish Laboratory, who has made a careful examination of existing data on the absorption of γ-rays, informs me that the evidence as a whole is more in accord with the theory of Klein and Nishina than with the earlier theories of Compton and Dirac. It is evident, however, that in view of the importance of the question, a careful determination is required of the absorption and scattering of γ-rays of as definite frequency as possible in order to distinguish between the various theories.

It is of interest to note that the absorption coefficient of the most penetrating type of radiation deduced by Millikan and Cameron from their experiments is in excellent accord with that to be expected on the Klein-Nishina theory for a quantum of energy 940 million volts—the energy demanded for the transformation of the internal energy of the proton into radiation. Although this agreement is suggestive, our theories of absorption are at present too uncertain to place much weight upon it. Even if subsequent experiment should prove the correctness of an absorption formula within a certain range of frequency corresponding to the γ-rays, there would still be the need of extrapolating the formula over a very wide range, say from quantum energies of 3 million volts to 1000 million volts, to include the ultra-penetrating rays observed in our atmosphere.

In addition, there are a number of new factors which may have to be taken into consideration when we are dealing with the passage of very high-frequency radiation through matter. In the ordinary theories, the scattering of the radiation is supposed to be confined to the extra-nuclear electrons, but if we are dealing with a quantum of energy corresponding to the order of 100 million volts, it is not unlikely that the nuclear electrons may be effective in scattering as well as the outer electrons. Such an effect is to be expected if the energy of the quantum is large compared with the energy required to release an electron from the nucleus. In addition there is always the possibility and even the probability that such energetic radiations or the swift electrons liberated by them may be able occasionally to disintegrate the nucleus of the atom in their path.

For all these reasons, it is evident that much more information is required before we can draw any but tentative conclusions as to the nature of the penetrating radiations in our atmosphere. So far, experiments have been mainly confined to measuring the ionisation produced in a sealed electroscope. Further experiments are required which will give us definite indication of the energy of the swift electrons present in the atmosphere, for this will give us valuable information on the maximum frequency of the radiation present, quite independently of the exact accuracy of our theories of absorption.

Continued observations made in a Wilson expansion chamber should throw much light on the nature of the particles which produce the ionisation in a closed vessel, and with the addition of a magnetic field of sufficient intensity the curvature of the tracks of β-rays should enable us to determine their individual energy. Experiments of an analogous kind have already been made with an expansion chamber by Skobelzyn, in order to determine the relative intensities of the main γ-rays emitted by radium C. In the course of these experiments he has observed on several occasions the trails of very energetic β-particles, probably arising from the ultra-penetrating radiation in our atmosphere. During the present year Prof. Hans Geiger has developed a modified form of β-ray counter which records each β-particle entering a vessel of considerable volume in any direction. This new method is so delicate that it may prove very useful in counting and even recording the number of β-particles produced by the penetrating radiation.

While it is to be hoped that in the years to come we may have available for study in our laboratories swifter β-rays and higher frequency radiation than we have to-day, we can scarcely hope in the near future to produce artificially radiations, atoms, and electrons which have an individual energy of the order of 100 million to 1000 million volts, such as are present in our atmosphere.

It is thus of great interest and importance to use every promising method of attack to throw light on the nature and origin of these penetrating radiations and the effects arising in their transmission through matter. The magnitude of the effects to be observed is small and not easy to measure with accuracy; but with the ever-increasing delicacy of methods of attack we may hope to gain much further information. The study of these extraordinarily penetrating radiations is not only of great interest in itself, but also for its promise of throwing new light on fundamental processes in our universe connected with the building up and destruction of atoms. It may take many years of faithful experiment before the evidence is sufficient to test the correctness of the numerous interesting speculations that have been advanced to account for the origin and nature of these radiations.

Copper in Antiquity.

ON more than one occasion attention has been directed to the work of the British Association Research Committee which is investigating the sources of Early Sumerian copper. The interim report which was presented at the recent Glasgow meeting of the Association is of exceptional interest. It embodies a report by Prof. C. H. Desch which would appear to point to a possible source from which copper reached Mesopotamia in early times. It is scarcely necessary to say that the quantity of copper and bronze objects found is one of the not least remarkable features of recent excavations on early sites in Sumeria. It has almost revolutionised our conception of the early stages in the growth of civilisation.

The method followed by the Committee has been to analyse chemically as many samples of ancient copper and bronze objects as could be obtained for comparison with the analyses of ores from the various areas in which supplies of copper might have been accessible to the Sumerians. Examples of early date from areas other than Sumeria have also been analysed for purposes of comparison. In the present report, for example, Prof. Desch deals with objects from Susa, Ur, Kish, Bahrein Island, Egypt, including the sheet metal of the statue of Pepy I, now in the Cairo Museum, and North Arcot, India. Specimens from Mohenjo-Daro are still under examination, and samples from other localities still await attention. Egyptian fragments from various sites supplied by the Ashmolean Museum, Oxford, too small for analysis, were examined spectroscopically. Ores were obtained from Anatolia, Persia, Arabia, and Egypt. Prof. C. O. Bannister, as well as Prof. Desch, has taken part in the work of analysis.

An analysis of three specimens of bronze from the first grave at Ur, dated about 3500 B.C., showed that notwithstanding their early date, they consisted of a tin bronze, with nickel as a characteristic impurity. The figures were as follows :—

	A per cent.	B per cent.	C per cent.
Copper . . .	84·18	85·13	85·01
Tin	12·00	11·78	14·52
Lead . . .	1·62	1·13	0·47
Nickel . . .	2·20	0·25	trace
Iron . . .	—	1·71	—

Specimens obtained from the excavations at Kish in 1928 also contained nickel, though in smaller quantities, while of specimens obtained in 1925, copper from Mound A (3000 B.C.) showed nickel 3·34 per cent, and bronze from Mound W (Nebuchadnezzar) showed of nickel a trace, with 4·65 of tin and 6·16 of iron. Samples from Tel-el-Obeid showed respectively nickel 0·12 (from the frieze) and 0·23 (a nail); but a nail from Iraq of 2000 B.C. yielded no nickel.

In no case was there antimony.

Bronze dated with some probability at 1200 B.C. obtained by Sir Flinders Petrie from tumuli in Bahrein Island, yielded nickel in two cases in a percentage of 0·27 and 0·52. These specimens in the quantity of sulphur present showed evidence of imperfect smelting, while the proportion of tin present in some was so high as to render the bronze too brittle.

Among the Egyptian samples, the sheet metal from the statue of Pepy showed a remarkably high percentage of nickel—1·06. The Egyptian specimens examined spectroscopically showed no traces of gold or nickel. Some were pure copper; others showed traces of iron and arsenic, with, in one case, tin 5·25 per cent. The North Arcot specimens had 0·25 per cent of nickel.

Prof. Desch quotes analyses of three objects by Von Bibra from the North-West Palace of Nineveh found by Layard, containing 0·18, 0·30, and 0·20 per cent of nickel respectively, while J. Sibelien found 0·28 per cent of nickel in a Sumerian statuette (about 3000 B.C.) and 0·43 per cent in a copper adze of the First Egyptian Dynasty.

Having these results in view, and having regard to the fact that nickel is by no means an invariable constituent in copper ores, the aim of the Committee is now to find an ore which would be likely to yield nickel in such proportions. Native copper from Angora has yielded copper 99·83, a trace only of tin, 0·17 of iron, and no trace of nickel, while native copper from Arghana with 97·08 of copper, 0·27 of tin, 2·13 of iron, has 0·03 of nickel. A copper chisel of the early dynastic period yielded copper 93·21 per cent, silver 2·51 per cent, gold 4·14 per cent, lead 0·05, and arsenic 0·06 per cent, and was therefore probably composed of native metal.

Ores from Persia, the Black Sea, and the Sea of Marmora, Cyprus, various parts of Egypt and Sinai, yielded no result, all being free from nickel.

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