contraction would probably be observed, which would not be converted into an extension until the whole of the internal surface had yielded.

The authors desire to place on record their indebtedness to Prof. J. E. Petavel, F.R.S., for many valuable suggestions in the course of this work.

The Attainment of High Potentials by the Use of Radium.

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The original aim of the work described in this note was to measure the energy and numerical importance of each of the many distinct kinds of β-particles emitted by a single radioactive substance. Calculation of the energy of a β-particle from observation of its deflection in a magnetic field* involves assumptions which are as yet insufficiently supported by experiment. Theoretically both the energies and distribution of the particles could be directly measured by giving a gradually increasing positive charge to the source of radiation; for, when the potential of the source is $+V$, electrons possessing energy less than eV will be drawn back to the source of radiation. Unfortunately, more than a million volts would be necessary to stop the fastest β-particles, and no method is at present known of maintaining such a high potential *in vacuo*. It was thought that this difficulty might possibly be overcome by using the active material itself in order to produce the high potential according to the principle employed in Strutt's radium clock.† If the source of radiation were perfectly insulated its potential would rise until the swiftest β-particles could no longer escape. The present note deals with experiments‡ made to test whether this method were practicable. It was found that high potentials were readily obtained, but the attempt to attain to a million volts failed through the difficulties of insulation encountered. But few experiments were completed, and many failed as the result of accident. This shows that, even if perseverance had been rewarded by greater success, technical difficulties, accentuated by

* Planck, 'Phys. Zeit.,' 1906, vol. 7, p. 753.

† Strutt, 'Phil. Mag.,' 1903, vol. 6, p. 588.

‡ A preliminary account of these experiments was communicated to the Manchester Literary and Philosophical Society, November 12, 1912.

every effort to improve the insulation, would probably have prevented the practical application of the method. It seemed, therefore, useless to pursue the matter further, until more is known of the reasons why the insulation of a vacuum breaks down.

In these experiments the source of β-radiation was 20 millicuries or more of purified radium emanation contained in a thin bulb—marked B in fig. 1—

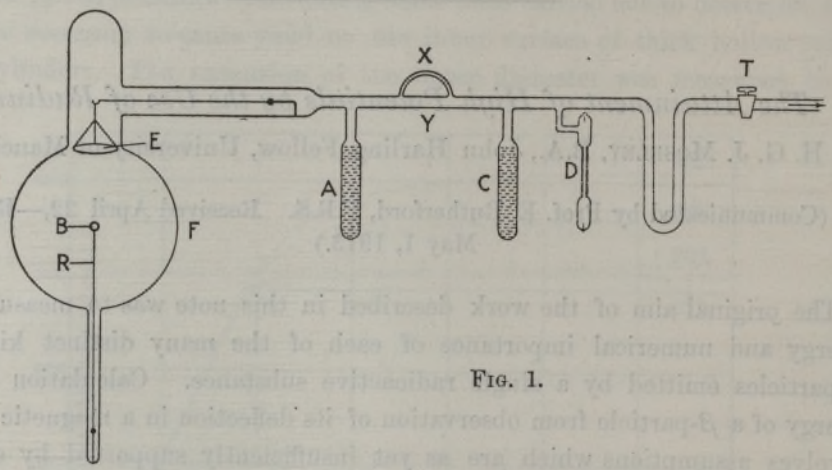

Fig. 1.

of about 1 cm. diameter. The bulb, which was just thick enough to stop all α-radiation, was supported by a fine silica rod R inside an exhausted glass flask F of 1 litre capacity. The rod, of diameter about 0·8 mm., was freshly drawn from transparent fused silica. The surface of the bulb and the flask was coated with silver, which was found to retain a trace of conductivity when subsequently heated to 400° C., though it then became almost transparent. The potential gained by the bulb was measured by a simple form of attracted disc electrometer, a circular aluminium disc being hung from the arm of a horizontal silica spring, the other end of which was soldered with aluminium to a projection from one of the glass walls of the flask. By observing with a microscope the displacement of the disc, the force of attraction exerted on it by the bulb was measured, and from this it was easy to calculate the charge and the potential acquired by the bulb. The force of a dyne displaced the spring by about 0·1 mm. The disc was hung just at the entrance to the mouth of the flask, so that the remainder of the flask wall served the purpose of a guard-ring.

In order to diminish the risk of discharge through any trace of gas left in the vessel, the greatest care was taken in the exhaustion of the flask. Instead of an attempt being made to measure the residual pressure in the apparatus, methods of exhaustion were followed which, in the hands of

others, have yielded the highest attainable vacua.* To remove water and other volatile substances the entire apparatus was subjected to prolonged heating at 400° C., and exhausted by a Gaede mercury pump. Everything was heated electrically, the main flask F being surrounded by a cylinder of sheet asbestos wound with nickel wire and insulated with kieselguhr, while the charcoal bulbs A and C and the connecting tubes were enclosed in small tube furnaces. At first, almost as soon as pumping ceased, the hydrogen and carbon monoxide lines appeared in the discharge tube D, which was used to test the degree of exhaustion. After some hours' heating, and after repeatedly filling the whole system with dried nitrogen and then re-exhausting, a few minutes' pumping sufficed to prevent the passage of a discharge in D, and this condition was then maintained for an hour or more after pumping had ceased. To obtain this result it was necessary to employ a U-tube cooled in liquid air to condense the vapours of mercury and tap-grease, and the charcoal in A and C, which was being heated all the time, had to be properly prepared. The preparation, which followed the directions given by Hupka,† consisted chiefly in heating freshly-made coconut charcoal to 450° *in vacuo*, until gas was no longer evolved; a tedious process, since the hydrocarbons are very slowly volatilised and decomposed. Before the final exhaustion the wide by-pass Y was sealed off. Then after five hours' pumping the tap T was closed, and C cooled in liquid air. After a further five hours the apparatus was sealed off at X, and quickly removed from the furnaces. A was then kept in liquid air during the course of an experiment. If all went well the exhaustion was completed in about 24 hours.

As soon as the apparatus had had time to cool, it was seen that the bulb was abruptly discharged every few minutes. The disc of the electrometer was first displaced by an amount which showed that the bulb was very highly charged, and then suddenly flew back to its original position, while in a dark room a yellowish-green flash was seen to light up the bulb, the rest of the interior of the flask remaining dark. The displacement of the disc immediately recommenced, at first slowly, since the force of attraction depended on the square of the attracting charge, then at an ever increasing rate, until the maximum was approached. The disc then began to move more slowly, at times it would falter or fall back a little, as if some slight discharge were taking place. Finally, without warning, came the complete discharge, the time occupied by the cycle being erratic, but

* Heuse and Scheele, 'Zeitschr. f. Instrumentenk.,' 1909, vol. 29, p. 46; Poynting and Barlow, 'Roy. Soc. Proc.,' 1910, A, vol. 84, p. 534.

† Hupka, 'Ann. d. Physik,' 1910, vol. 31, p. 169.

corresponding roughly with the interval expected having regard to the quantity of active material and the capacity of the system. The thin disc, if not in metallic connection with the flask, gained a free positive charge, which pulled it back towards the neighbouring silvered surface; a difficulty easily overcome by occasionally tilting the apparatus slightly. The bulb could be discharged at will by directing on to the apparatus a powerful beam of X-rays, the necessary charge being doubtless carried to the bulb by the swarm of electrons released from the surface of the flask.

A preliminary experiment made with simpler apparatus showed that a potential of the order of 150,000 volts could readily be obtained. In the first successful attempt to use the apparatus described above, the bulb, of diameter 9 mm., was made of quartz. As soon as the apparatus was completely exhausted a spark perforated the bulb and the radium emanation began to diffuse out and condense on the cooled charcoal. It was several days before the greater part of the emanation had been transferred, so that the size of the hole, calculated* from the rate of effusion, must have been only of the order of 10^{-4} mm. This accident appeared not to affect the discharge potential, which was found to be $1{\cdot}5 \times 10^5$ volts, and remained the same even when most of the emanation had left the bulb. The experiment was repeated with a glass bulb of 1 cm. diameter through which a platinum wire was sealed, in order to prevent the passage of a spark through the glass. The tip of the bulb was fixed by the wire into a small silica tube fused on to the silica rod. The maximum discharge potential observed was $1{\cdot}7 \times 10^5$ volts, but this figure was probably slightly over-estimated, since the silica tube if charged would itself have attracted the disc appreciably. In each case the discharge potential decreased as soon as the charcoal was heated to room temperature, but was still of the order of 10^5 volts. This decrease is a strong indication that the sudden discharge, which always limited the potential, took place through the residual gas and not along the silica rod. The slow and irregular rate of charging at high potentials may have been due in part to conduction along the silica. The number of particles escaping must also have been somewhat diminished, since 160,000 volts will turn back any particle emitted with velocity less than 0·65 that of light.

Study of the experimental circumstances of discharge in high vacua has been singularly neglected. The only systematic work on the subject is that of Madelung.† This author, working with parallel electrodes at distances up to 0·4 mm., concluded that in the highest vacua a discharge takes place as

* Knudsen, 'Ann. d. Physik,' 1909, vol. 28, p. 999.

‡ Madelung, 'Phys. Zeit.,' 1907, vol. 8, p. 68.

soon as the electric force at the surface of the electrodes exceeds 3 or 4×10^5 volts per centimetre. The highest potential used by him was only about 12,000 volts, but his results showed clearly that under his conditions the discharge could not be explained by the ordinary theory of ionisation by collision in gases. In the present experiments there can be no doubt that the process of exhaustion was really effective, as special tests were made to guard against the possibility of mistake. The residual pressure was therefore so small that ordinary ionisation by collision was out of the question.

When a bulb of 9 mm. diameter is charged to a potential of $1{\cdot}5 \times 10^5$ volts, the electric force at the surface is $3{\cdot}3 \times 10^5$ volts per cm., and the agreement between this figure and that found by Madelung may well be more than a coincidence. Again, in the one experiment the tip of a platinum wire projected from the glass bulb, and the failure of this point, at which the electric force must have been enormous, to promote discharge is paralleled by Madelung's observation that the discharge potential was much higher between pointed electrodes than between parallel plates at the same distance. The nature of this discharge at very low pressures is still obscure, but it is probably essentially the same as the discharge found by many observers to pass in air at less than the minimum spark potential between electrodes very close together. This latter discharge has been the cause of much controversy; partly because some observers have looked for a visible spark, while others have been content with the passage of a minute current; partly on account of experimental difficulties introduced by the use of air and consequent restriction to minute spark-gaps; and partly because the discharge seems to be much influenced by the nature and condition of the electrodes. With varying length of spark-gap the discharge takes place when the electric force at the electrodes reaches a fixed limiting value, which is apparently uninfluenced by the presence of any kind of gas.* Various observers† using different electrodes have found values ranging from rather more than 10^6 up to 10^7 volts per centimetre, while Almy‡ obtained no visible discharge with an electric force of nearly 2×10^7 volts per centimetre. It is not clear why the maximum electric force found by Madelung and in the present experiments should be so much lower, but very possibly the area of the electrode surface is here a factor of importance.

For these reasons it was hoped that the discharge might be prevented by

* Hobbs, 'Phil. Mag.,' 1905, vol. 10, p. 617 ; G. Hoffmann, 'Phys. Zeit.,' 1910, vol. 11, p. 961.

† Hobbs, *loc. cit.*; G. Hoffmann, *loc. cit.*; Earhart, 'Phil. Mag.,' 1901, vol. 1, p. 147 ; Shaw, 'Roy. Soc. Proc.,' 1903, vol. 73, p. 337 ; Kinsley, 'Phil. Mag.,' 1905, vol. 9, p. 692 ; Rother, 'Phys. Zeit.,' 1911, vol. 12, p. 671.

‡ Almy, 'Phil. Mag.,' 1908, vol. 16, p. 456.

increasing the size of the bulb, and so reducing the surface intensity of electrification. An experiment was, therefore, tried using a bulb of 5 cm. diameter. The electrometer spring was made very much stronger in anticipation of a much greater force of attraction, but otherwise nothing was altered. Mr. Baumbach, the University glass blower, successfully undertook the difficult task of assembling the apparatus. Owing to the increased capacity of the bulb it charged up much more slowly than before. Instead, however, of discharging itself at intervals, it now became charged to an almost constant potential, which it retained, except when artificially discharged by the use of X-rays, for at least three weeks. During that time this potential gradually rose from 10^5 to $1{\cdot}1 \times 10^5$ volts, while the current carried away by the β-particles fell from about 10^{-11} amperes to 2 per cent. of that value, owing to the decay of the radium emanation. The potential was uninfluenced by the temperature of the charcoal bulb, and there can be little doubt that it was limited by a leak along the silica support, which was now stouter and less scrupulously cleaned than before. This curious case of the potential being independent of the current carried by the silica strongly resembles conduction in a gas at a potential just below that required to produce a spark. There variation of the current over wide limits is accompanied by very slight change in the potential, and perhaps the conduction in the silica had a similar origin. In the event of this method of maintaining a constant high potential proving of practical use, much time could probably be saved by cutting short the process of exhaustion.

We see then that a radioactive substance may by the emission of β-radiation charge itself positively to a potential difference of more than 150,000 volts from its surroundings. This fact provides a striking direct proof of the large amount of energy involved in the expulsion of a β-particle. It also extends somewhat our knowledge of the insulating properties of a vacuum. Previously Hupka (*loc. cit.*) had shown that two plates could in a highly exhausted chamber be maintained by means of an influence machine at a potential difference of 90,000 volts, without any discharge taking place. I am indebted to his paper for many useful suggestions.

In conclusion I wish to thank Prof. Rutherford for his kind interest in the progress of this work.