PROCEEDINGS OF THE ROYAL SOCIETY A | MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

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Proc. R. Soc. Lond. A 1930 **129**, 477-489
doi: 10.1098/rspa.1930.0169

Experiments with High Velocity Positive Ions.

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(Communicated by Sir Ernest Rutherford, P.R.S.—Received August 19, 1930.)

[Plate 21a.]

1. *Introduction.*

It would appear to be very important to develop an additional line of attack on problems of the atomic nucleus. The greater part of our information on the structure of the nucleus has come from experiments with α-particles and if we can supplement these with sources of positive ions accelerated by high potentials we should have an experimental weapon which would have many advantages over the α-particle. It would, in the first place, be much greater in intensity than α-particle sources, since one microampere of positive ions is equivalent, so far as numbers of particles is concerned, to 180 grams of radium equivalent. It would in addition have the advantage of being free from penetrating β and γ rays which are a complication in many experiments, whilst the velocity would be variable at will.

The main difficulty in obtaining such sources lies of course in the production and application of the very high potentials necessary to accelerate the particles if velocities approaching that of the α-particle are to be obtained. For example, α-particles from polonium have an energy corresponding to 5·2 million electron volts and a potential of 2·6 million volts would be required to give a helium nucleus an equal amount of energy. We have therefore to decide what is the minimum acceleration voltage at which we can usefully work, since the experimental difficulties increase very rapidly with increasing voltage. In making this decision we are naturally guided by the recent theoretical work of Gamow* on the "Theory of Artificial Disintegration." On Gamow's theory the probability of an α-particle of velocity v entering a nucleus of atomic number Z, after coming within the effective radius of the nucleus, is

$$W = e^{-\frac{16\pi\varepsilon^2 Z}{hv} J_k},$$

where J_k is a function varying slowly with v and Z. It is clear, therefore, that for particles of equal energy the lighter particle has the greater chance of

* 'Z. Physik.,' vol. 52, p. 514 (1929).

penetration into the nucleus, so that we should choose protons as our source of positive ions for this reason.

Values of W for a proton of 300 KV. entering different elements are given in Table I. We tabulate also their closest distance of approach for a head-on collision on the classical theory.

Table I.

Element.	H.	Be.	B.	C.	Al.	α-particle from Polonium in Al.
W	—	$6 \cdot 2 . 10^{-3}$	$1 \cdot 2 . 10^{-3}$	$2 \cdot 1 . 10^{-4}$	(0) 10^{-9}	0·65
b	$4 \cdot 8 . 10^{-13}$	$1 \cdot 9 . 10^{-12}$	$2 \cdot 4 . 10^{-12}$	$2 \cdot 88 . 10^{-12}$	$6 \cdot 2 . 10^{-12}$	—

The voltage of 300 KV. was chosen because it appeared quite possible to begin work on a laboratory scale with voltages of this order and to develop vacuum tubes which would withstand such potentials. It appears from this table that there is at any rate some chance of obtaining results of interest in experiments on artificial disintegration and on scattering of protons by different elements. From unpublished results of Blackett the range of a 300 KV. proton in air should be about 5 mm., so that it might be possible to study their effects in the Wilson expansion chamber.

In addition to experiments of this type, great interest attaches to experiments on the radiation produced by protons on impact with matter. So far experiments have been carried out with protons up to 55 KV.* velocity and no evidence has been obtained of any continuous or characteristic radiation. The experiments of Bothe and Franz† on the Excitation of Characteristic Radiations by Polonium α-particles show, however, that the intensity of the radiation varies approximately as the ninth power of the velocity of the particle so that it is well worth while investigating the problem with 300 KV. protons. The very much greater intensity attained with proton sources might be expected to offset the decrease in intensity due to the lower velocity. There is also the very interesting point as to whether a nuclear radiation of the type discovered by Bothe and Becker,‡ resulting from the bombardment of light elements with polonium α-particles, can be excited by proton impacts.

* Barton, 'J. Franklin Inst.,' vol. 209, p. 1 (1930); Gerthsen, 'Ann. Phys.,' vol. 85, p. 881 (1928).

† 'Z. Physik,' vol. 52, p. 466 (1928).

‡ 'Naturwiss,' August 8, 1930.

2. *Methods of Production of High Velocity Positive Ions.*

The problem may be divided into two parts: first, the production of a stream of positive ions in a form suitable for acceleration, and second, the method of acceleration. It is unfortunate that sources of protons cannot be obtained as simply as sources of positive ions of the alkali metals. It was found possible, for example, to develop a very simple tube in which sources of sodium ions obtained from a Kunsman mixture could be accelerated by potentials up to 200 KV. and there is no doubt that this tube would have withstood the potentials of 300 KV. which were later available. In the search for an equally simple source of protons, experiments were made similar to those of Barton (*loc. cit.*) on the production of protons by the diffusion of hydrogen through a tube into a strong electric field. A platinum tube of diameter 0·25 mm. was surrounded concentrically by a cylindrical cathode. The platinum tube was heated to 1350° C. and hydrogen allowed to diffuse through. A potential of 20 KV. was then applied between tube and anode giving a field of 400 KV. per centimetre at the surface of the tube, a field of the order of fifty times that used by Barton. It was thought possible that increased ionisation of the issuing gas might result, but no positive result was obtained.

We had thus to fall back on the low voltage arc or the canal ray tube as a source of hydrogen ions. The low voltage arc has the advantage that the ions produced are more homogeneous in velocity than the ions from a canal ray tube, but it was found that the pencil of ions so produced was very much less intense at the end of the metre path necessary for the accelerating chamber, than in the case of the canal ray tube ions. With the canal ray tube, sources of ions of several micro-amperes could be obtained after acceleration and this method was therefore chosen.

In considering methods of acceleration of the ions, four sources of potential suggest themselves for consideration—Tesla coils, impulse voltages, low frequency alternating potentials and rectified steady potentials. If it is desired simply to obtain the highest possible potentials with the minimum of trouble then the Tesla coil is obviously the ideal solution. Breit and Tuve* claim for example, to have produced voltages of several millions with a Tesla coil wound on a metre length of Pyrex tubing and experiments by Dr. Allibone† in the Cavendish Laboratory have shown that the Tesla coil can be used successfully for certain types of experiments with electrons. It has, however, the serious disadvantage that the average time during which the maximum

* 'Phys. Rev.,' vol. 35, p. 51 (1930).

† In course of publication.

voltage occurs is usually only about one-thousandth of the total time, so that the intensity of the stream produced is very low when dealing with a limited source of ions as in positive ion work. Its main application would appear to be in experiments of the Wilson chamber type in which only very weak sources of ions are required.

The impulse generator allows a unidirectional voltage impulse to be obtained by connecting in series a number of condensers charged in parallel. The maximum value of the impulse may reach several million volts, its duration being several micro seconds. This method suffers still more seriously from the disadvantages of the Tesla coil in its short time of application, but has the advantage over the Tesla coil in that most dielectrics will withstand a much greater stress for a few micro seconds than when subjected to an oscillatory voltage of the Tesla type.

By the third method, low frequency alternating potential, voltages of over a million may be obtained by connecting transformers in cascade, the only limitation to the voltages obtainable being expense and space. If alternating voltages are used for the acceleration of the ions, both positive and negative ions will be obtained from a canal ray tube source and ions of all velocities will be present. This would necessitate, first, a rectified source of excitation for the canal ray tube since high voltage electrons cause very serious interference with all experiments, due to the X-rays produced. Secondly, it would be necessary to apply magnetic analysis to obtain a homogeneous beam of ions and the source obtained would be weakened. It is clear therefore that the ideal accelerating voltage is a steady potential produced by rectifying the current from a low frequency transformer. Since the current required is only a few micro amperes the potential may be smoothed very completely by a condenser of a few thousandths of a micro farad capacity and the stream of ions produced may be expected to have a very uniform velocity. It was therefore decided to construct a thermionic rectifier for 300 KV. which would at a later stage allow of extension to 600 KV. if this was required by the experiments. For this purpose the well-known circuit of fig. 1 is used in which two kenetrons A are connected in series to withstand the doubled voltage in the non-conducting half cycle. The canal ray tube is excited by a separate 60 KV. transformer F, the whole of which is raised to a potential of 300 KV. above earth, the primary being supplied by a special insulation transformer G.

If it is desired at a later stage to double the voltage it would be necessary to add a second Kenetron unit, and condenser, with an insulating transformer to supply the primary of the high tension transformer.

Having decided on a unit to generate 300 KV. the difficulty at once arose that no commercial rectifiers existed which would withstand voltages of more

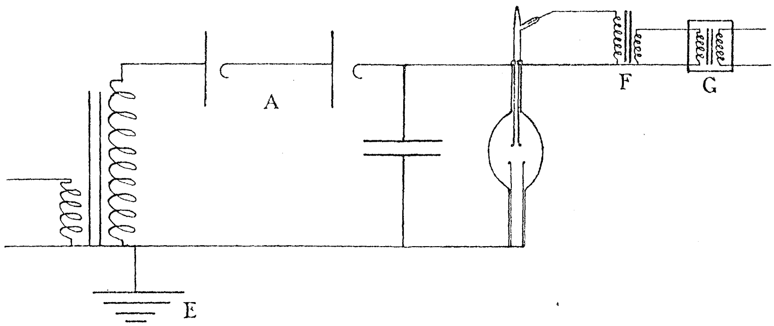


Fig. 1.

than 220 KV., so that three or four Kenetrons would be required for the purpose, with double the number for the higher voltage. This complication is very undesirable if only on grounds of expense, for puncture of one Kenetron may lead to the failure of the rest. As, however, the experiments of Dr. Allibone on high voltage Lenard tubes had resulted in the development of a continuously evacuated tube which would withstand 350 KV., it seemed certain that a continuously evacuated Kenetron could be produced which would enable the necessary 300 KV. to be obtained with one unit. After a few experiments with different sizes of tubes and different electrode arrangements, we were finally successful in developing a suitable type of rectifier.

For the supply of the high voltage, a transformer giving 350 KV. with one end earthed was designed by the Research Staff of the Metropolitan-Vickers Electrical Company, particular attention being paid to compactness in design. The current output of the transformer is 60 milliamps, an output necessitated not by the small experimental current required but by the capacity current of the apparatus at high potential, a capacity of 100 cm. requiring a charging current of 15 milliamperes at 250 KV. The transformer primary is excited by a motor generator set giving smooth control of the voltage by variation of the generator field, special control switch gear being installed to eliminate switching surges. The secondary voltage is determined by rectifying and measuring the charging current of a small condenser formed by a band on the outside of the transformer bushing and the high tension lead.

A unipivot galvanometer G combined with a frequency meter allows the voltage to be determined with an accuracy of 1 per cent., a calibration being carried out in the first place with a standard sphere gap.

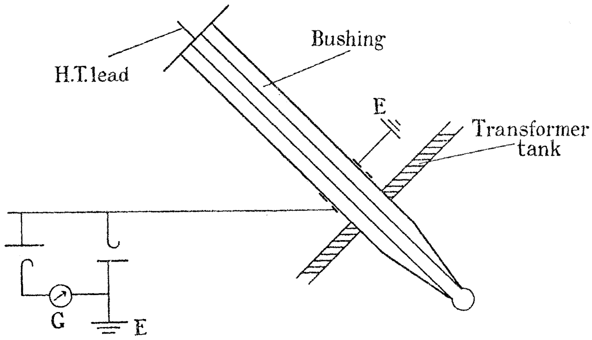


FIG. 2.

3. *Rectifying Apparatus.*

A considerable amount of experimental work was carried out before a suitable design for the thermionic rectifiers was evolved. The sparking distance for 300 KV. between points in air is 100 cm. and the tubes used must be longer than this to allow room for suitable corona shields at each end. If the size of the bulb on the tube is too small the glass gets charged up in isolated patches by auto electronic emission from the electrodes, even though the electrodes have been designed to avoid sharp corners and have been well polished. As the voltage is raised, surface creepage sparks (" Gleitfunken ") result and can be seen running from one side of the bulb to the opposite side, puncture usually following very soon. To prevent this, the bulb should be large and the glass should be thick and of a high dielectric strength. On the recommendation of Dr. Gunther Schultze, the bulbs finally used were blown from a hard " molybdenum " glass by the Jena Glaswerke. The bulb diameter was 30 cm. and the stems were 5 and 9 cm. in diameter respectively.

Various types of filament and electrode design were tried. In order to prevent electrons from reaching the walls of the bulb, the anodes were made from nickel plated copper vessels which at first almost completely surrounded the cathode. To prevent the large electrostatic forces from distorting the filament, the latter was placed just inside the end of a steel shield. This produced a poor type of characteristic as shown by curve A in fig. 3, the voltage drop being excessive due to space charge. The filament was then exposed by pushing up the shield and, after a number of trials, it was found that a V-shaped filament, supported at the ends and in the middle, was not deformed by the voltages used. The filament was made of 0·25 mm. tungsten wire and was placed about 5 cm. in front of the anode, the characteristic for this arrangement being given by curve B, fig. 3. All the metal parts were outgassed *in vacuo* before assembly and the anodes were outgassed *in situ* by electron bombardment

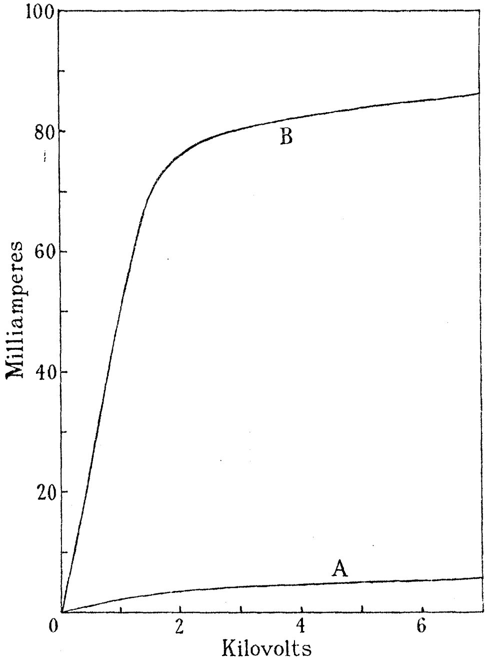


FIG. 3.

from the filament. With this type of rectifier it was found possible to produce 150 KV. direct current and thus two in series should give 300 KV. direct current.

Since the rectifiers are to be continuously evacuated and since each end of them has to be at high potential, it is necessary to pump out through a tube which will stand the full potential. The most convenient arrangement appeared to be to join the two rectifiers end to end and to pump out through a third bulb similar to that used for the rectifiers. The whole forms a large T-piece and is shown to scale in fig. 4. As shown in this diagram, the insulation bulb has tubular electrodes fitted, which distribute the electrical stress properly and so prevent puncture of the glass. The pump used is a three-stage oil diffusion pump designed by Burch.* The speed of the pump is 20 litres per second and full advantage of this can be taken as no liquid air trap was

* 'Proc. Roy. Soc.,' A, vol. 123, p. 271 (1929). (We are indebted to Metropolitan-Vickers Electrical Company for supplying us with several of these pumps before they had been put on the market.)

necessary. This type of pump has been found to be very satisfactory. Its speed was evident during the outgassing of the anodes. The bombarding

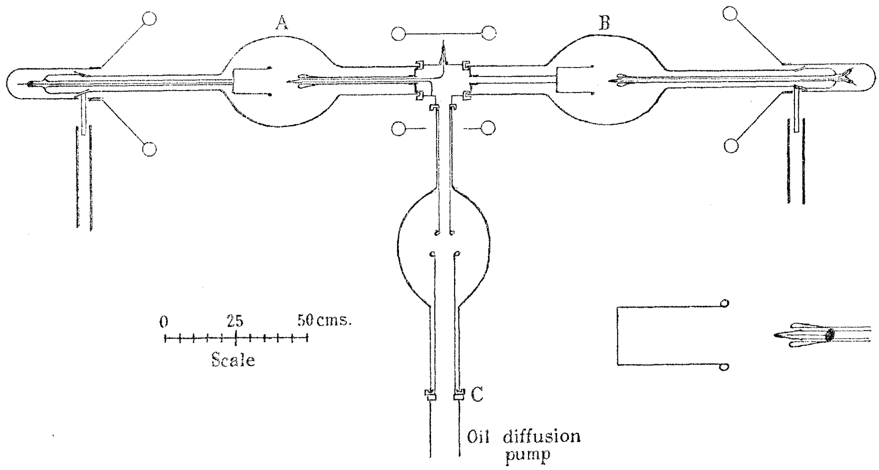


Fig. 4.

potential used caused the tubes to go " soft " when the gas was liberated. On switching off this potential for only a few seconds, the large volume of gas in the three bulbs was found to have been completely exhausted. The only disadvantage which oil has as compared with mercury is that it is necessary to be careful that air is not admitted to the apparatus while the oil is hot.

The three bulbs are joined together by waxing them into a steel T-piece. The insulation bulb carries most of the weight and is supported directly on top of the pump. It is connected to the latter by a flat steel to steel ground joint to which it is waxed. The outer ends of the bulbs are supported on long Bakelite tubes. This general design of rectifier results in an economy of space, of a pump and of a bulb. It has the further advantage that if one rectifier accidently goes " soft " the other goes " soft " too, and it thus avoids puncture of the glass by the extra potential thrown upon it. Corona shields, as shown in fig. 4, are fitted at each end of the tubes and in the middle to prevent puncture of the glass stems. At first these were placed at the extreme ends of the rectifiers and a number of punctures were obtained through the glass at the junction of the stem to the bulb. It was found that this could be avoided by moving the shields considerably nearer to the bulbs of each rectifier. When a puncture through the glass occurs, it was found that the leak produced can be very readily stopped by painting over the hole with cellulose enamel.

The filaments were originally heated from oil-immersed transformers, but as it proved impossible to get these to stand a potential greater than 250 KV. without using excessive dimensions it seemed simplest to substitute accumulators. These are placed inside round boxes to prevent brushing and are insulated from earth by Bakelite cylinders.

In order to secure an equal distribution of potential between the rectifiers, it is necessary that the various capacities present should be properly balanced. It can be seen that the capacity between the electrodes in the insulating bulb and the capacity of the accumulators for heating the filament in bulb A are effectively in parallel with the capacity of bulb B. The capacities involved are small and the following appeared to be the simplest way of obtaining the correct size of balancing condenser. A sphere gap C, D was connected to the extreme ends of the rectifiers A and B as shown in fig. 5. A third sphere

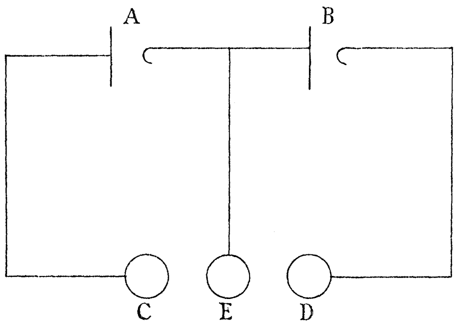


Fig. 5.

E was suspended symmetrically between the spheres C and D by fine wire and was connected to the junction of the rectifiers A and B. A small voltage was then applied to the rectifiers and if the potential across A exceeded that across B, then the force between C and E was greater than that between D and E, with the result that E would move towards C. In this way it was possible to adjust the capacity of the balancing condenser much more accurately than was required. The spheres could then be removed without disturbing the balance as they had introduced equal capacities across the two rectifiers. The balancing capacity required was about 40 cm., and was made from about a dozen glass dielectric, parallel plate condensers connected in series. These were stacked one on top of the other and separated by distance pieces so that spark over in air would not occur between the first and last condensers.

The current from the rectifiers is smoothed by a 0·002 μ F condenser.

4. *Design of Tube for Producing Fast Protons.*

The direct potential obtained by the method just described, is applied to a large bulb similar to that used for the rectifiers. As shown in fig. 6, the bulb is

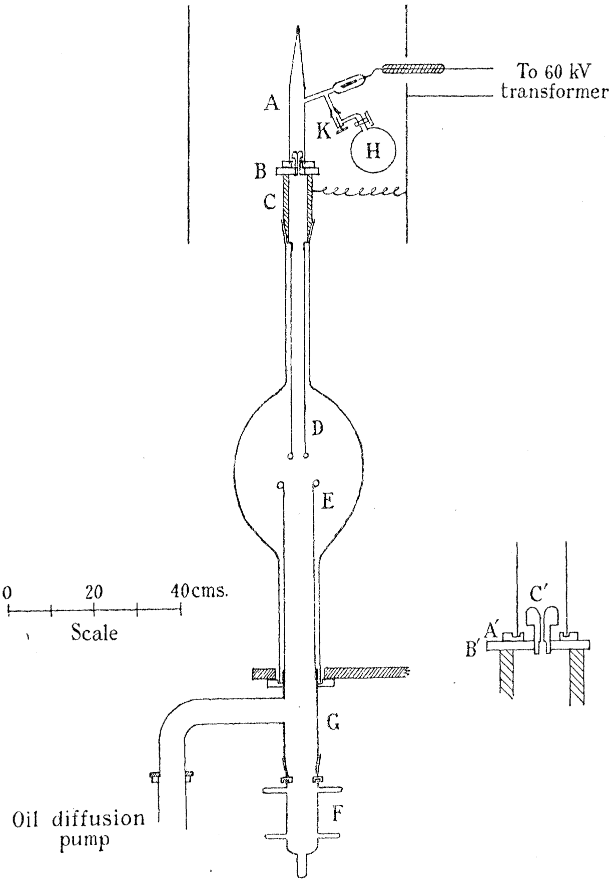


Fig. 6.

fitted with tubular electrodes, D, E of the type used in the insulation bulb, the upper electrode D being screwed to the steel section of a steel to glass ground joint connecting the bulb with the canal ray tube. The canal ray tube, A, is of the Wien type and is waxed into a groove in a flat steel ground joint A′. This can be moved over another ground flat surface B′, which is soldered to the top of the tube C. A good vacuum-tight joint can easily be made by running a little low vapour pressure grease* round the outside. By the adoption of

* Burch, *loc. cit.*

this device, the canal ray tube can be moved with respect to the anode C′, whilst the tube is under vacuum and very accurate adjustment is possible. The importance of this adjustment is shown by our obtaining an increase by a factor of five in the positive ion current reaching the experimental chamber F.

The experimental chamber consists of a length of 3-inch diameter glass tubing with suitable side stems, waxed into one section of a conical steel to steel ground joint. The other section of the joint is soldered to a wax cup holding the accelerating tube. The joint is made tight by running " picein " over it with a small flame. A short piece of 2-inch diameter steam pipe connects the tube G to a fast Burch oil diffusion pump of the same pattern as used on the rectifiers. Very fast pumping is thereby attained.

The positive ions are produced by a discharge in hydrogen excited by an alternating voltage of between 40 and 60 KV. The positive ions pass through a canal 1·5 mm. in diameter and 10 mm. long, the electrode shape being made identical with that used by Dr. Aston in his mass spectrograph. After passing through the canal the stream of ions pass down the axis of the tubular electrode D and are accelerated to a speed corresponding to the potential applied to the tube when they reach the space between the electrodes D and E. A continuous flow of hydrogen from a storage bulb is admitted to the tube through a variable leak of the Kaye type.

In preliminary experiments a diaphragm was placed in the tube C to define the beam more closely. With this arrangement it proved to be necessary to use an additional diffusion pump to evacuate the space between the anode and the diaphragm, as without this additional pumping a great deal of neutralisation of the ions occurred. Fortunately it was found possible to remove this diaphragm altogether and dispense entirely with the extra pump, the Burch pump being quite capable of dealing with the leak with a potential of 300 KV. on the accelerating bulb. The addition of a pumping system at a potential of 300 KV. above earth would have been a serious complication in the apparatus.

The transformer for exciting the canal ray tube is raised to a potential of 300 KV. by the rectifiers and has to be supported on an insulating pedestal and shielded from corona by a cylindrical sheet of galvanised iron. As shown in fig. 1 its primary winding is excited by a one to one insulation transformer of the type described by Blackett and Hudson.* A spacing of 5 inches is used between primary and secondary and the whole is immersed in a Bakelite tube filled with very carefully purified transformer oil.

* ' J. Sci. Instruments,' vol. 5, p. 391 (1928).

As the canal ray tube is at a high potential above earth and has a number of sharp-edged metallic parts it is fitted with a corona shield of galvanised iron. A photograph of the whole apparatus is shown on Plate 21A.

5. *Operation of the Apparatus.*

On starting up the apparatus after several hours' rest we find that the rectifiers usually go soft at a comparatively low voltage, perhaps 80 KV. Immediately the discharge occurs the transformer voltage drops to a very small value for a few seconds until the pumps have dealt with the gas evolved. The voltage will then rise again and may be increased to perhaps double the value until a further evolution of gas occurs. After 1 or 2 minutes operation, stable working can be obtained. The hydrogen is then admitted and the position of the canal ray tube adjusted to give a maximum current in the experimental chamber. Once adjusted, of course no further movement is required in subsequent experiments. The pressure in the tube is next adjusted by the Kaye leak to give a maximum current in the experimental chamber. This usually occurs when the pressure is such as to cause green fluorescence over most of the glass, the potential applied then being 40 to 50 KV. and the current through the tube about one-third of a milliampere. It is usually possible to obtain a total current to a collecting electrode in the chamber F of the order of 10 microamperes. Unfortunately the greater part of this is due to secondary electron emission, and the application of a retarding potential to prevent escape of the secondaries reduces the total current by a factor of five.

Experiments were first carried out with a Willemite screen in the experimental chamber to determine the spread of the stream of ions. It was found that, as the accelerating voltage was increased, focussing of the stream occurred at about 80 KV. accelerating potential. The stream then produces a star-shaped pattern on the screen which disappears as the voltage is increased still higher. It seems probable that this focussing is produced by the radial component of the accelerating field inside the high tension accelerating electrode D, since the corresponding radial field in the low tension electrode E will have a negligible effect owing to the high velocity of the ions at this point. If this explanation is correct, it would appear possible to obtain focussing at any desired velocity by choice of the geometry of the accelerating electrodes. At the highest voltages, the stream was concentrated in a circle about 4 cm. diameter, the distribution of intensity being very clearly shown by the discoloration of a metal diaphragm placed in the path.

A magnetic analysis of the stream was carried out in order to determine the relative numbers of protons and molecules. A narrow beam was defined by a diaphragm and the protons and molecules were collected on separate targets after deflection. It was found that with the pressures used in the discharge tube, the number of protons was approximately equal to the number of molecules.

6. *Experimental Work in Progress.*

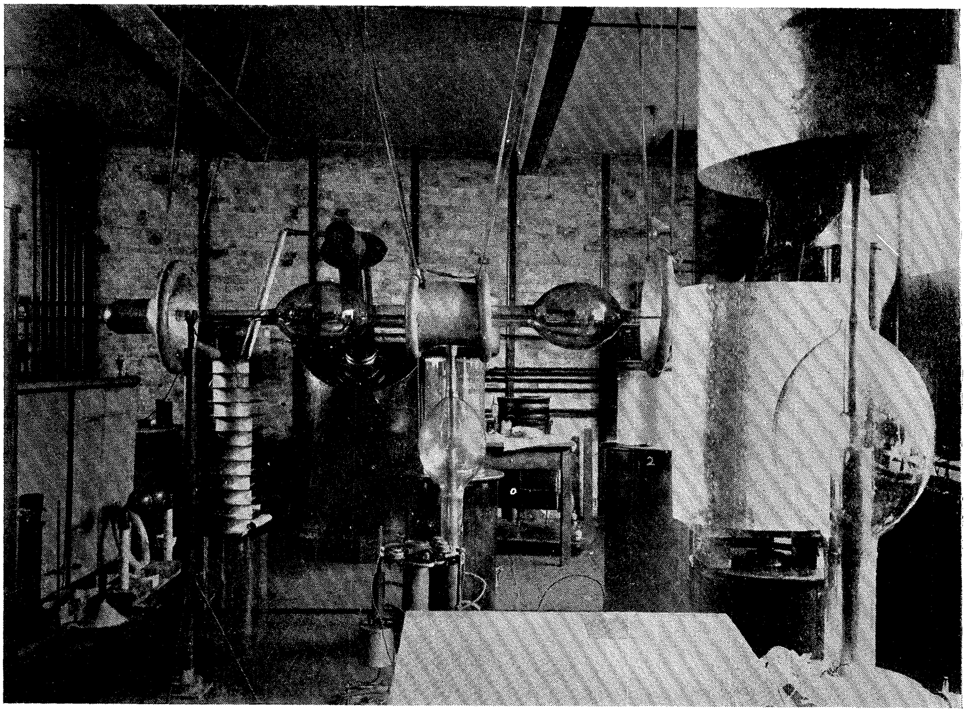
Experimental work of a preliminary character has been carried out with the mixed stream of protons and molecules at voltages up to 280 KV. in order to decide whether any radiation is produced by their impact on matter.

Using targets of lead and a beryllium salt successively, very definite indications of a radiation of a non-homogeneous type were found, using a gold leaf electroscope as a detector. By absorption measurements, the average hardness of the radiation from lead at 280 KV. would appear to be about 40 KV., but harder components were present which will require further investigation before any definite statement can be made. Control experiments were carried out to eliminate the possibility of the radiation being produced by spurious sources such as the canal ray tube or secondary electrons. The intensity of the radiation was of the order of one ten-thousandth of that produced by an equal electron source and increased extremely rapidly between 250 and 280 KV. No marked difference in intensity was observed between the radiation from beryllium and lead.

We are very much indebted to Mr. A. P. M. Fleming, Mr. G. McKerrow, Mr. B. L. Goodlet and other members of the research staff of the Metropolitan-Vickers Electrical Company for very considerable technical assistance and for the loan of apparatus.

One of us (E. T. S. W.) is indebted to the Royal Commissioners for the Exhibition of 1851 for the grant of an Overseas Research Scholarship.

We have finally to express our thanks to Sir Ernest Rutherford for his encouragement and advice throughout this work.



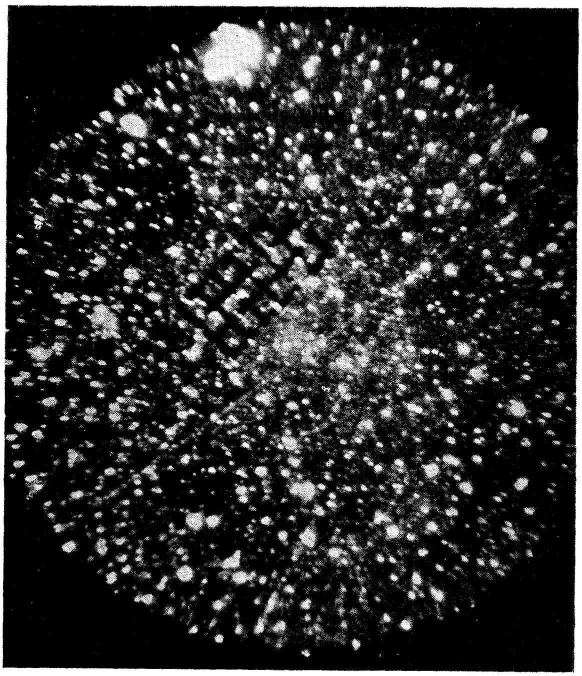
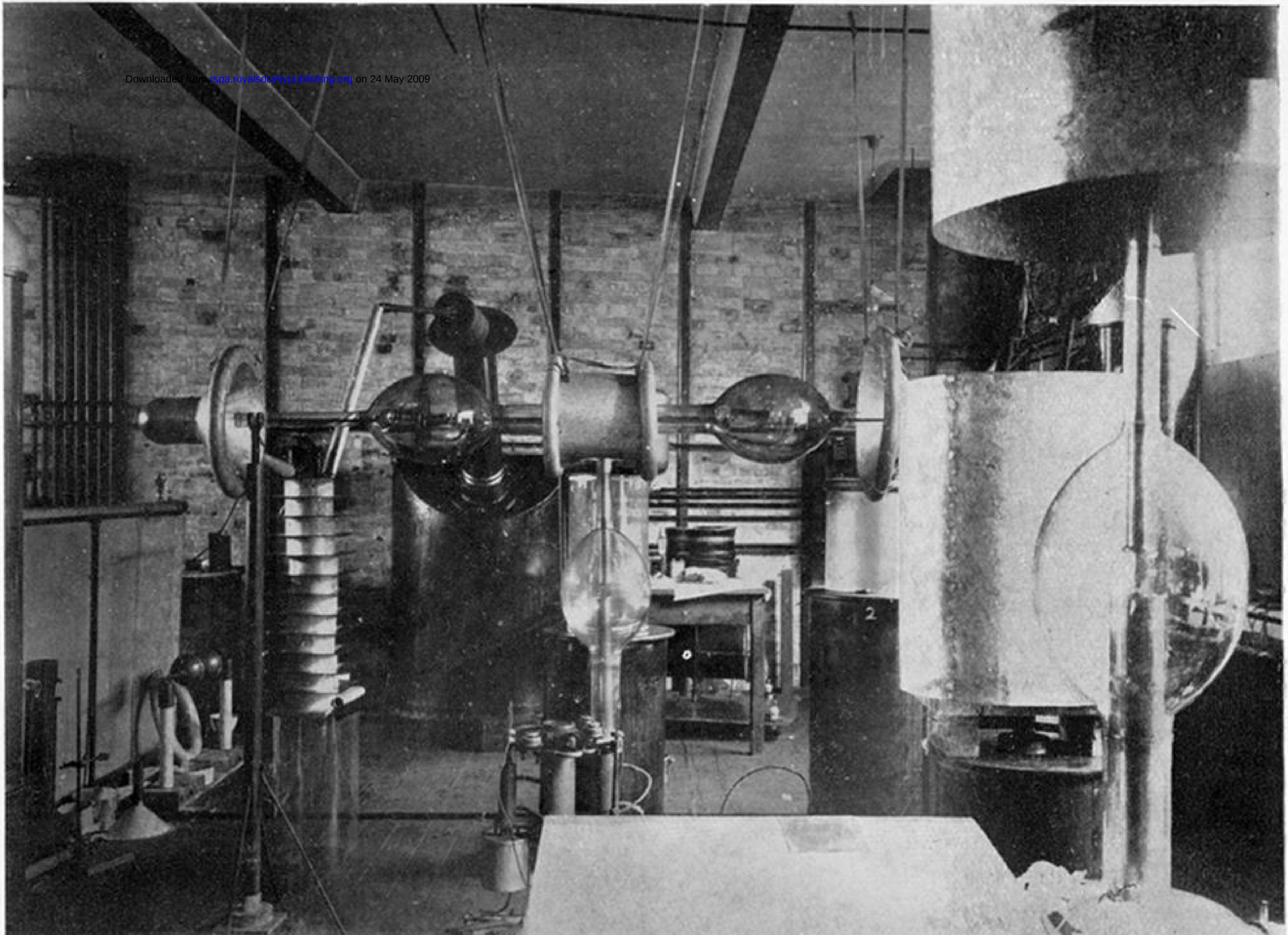


FIG. 3.

(*Facing p.* 490.)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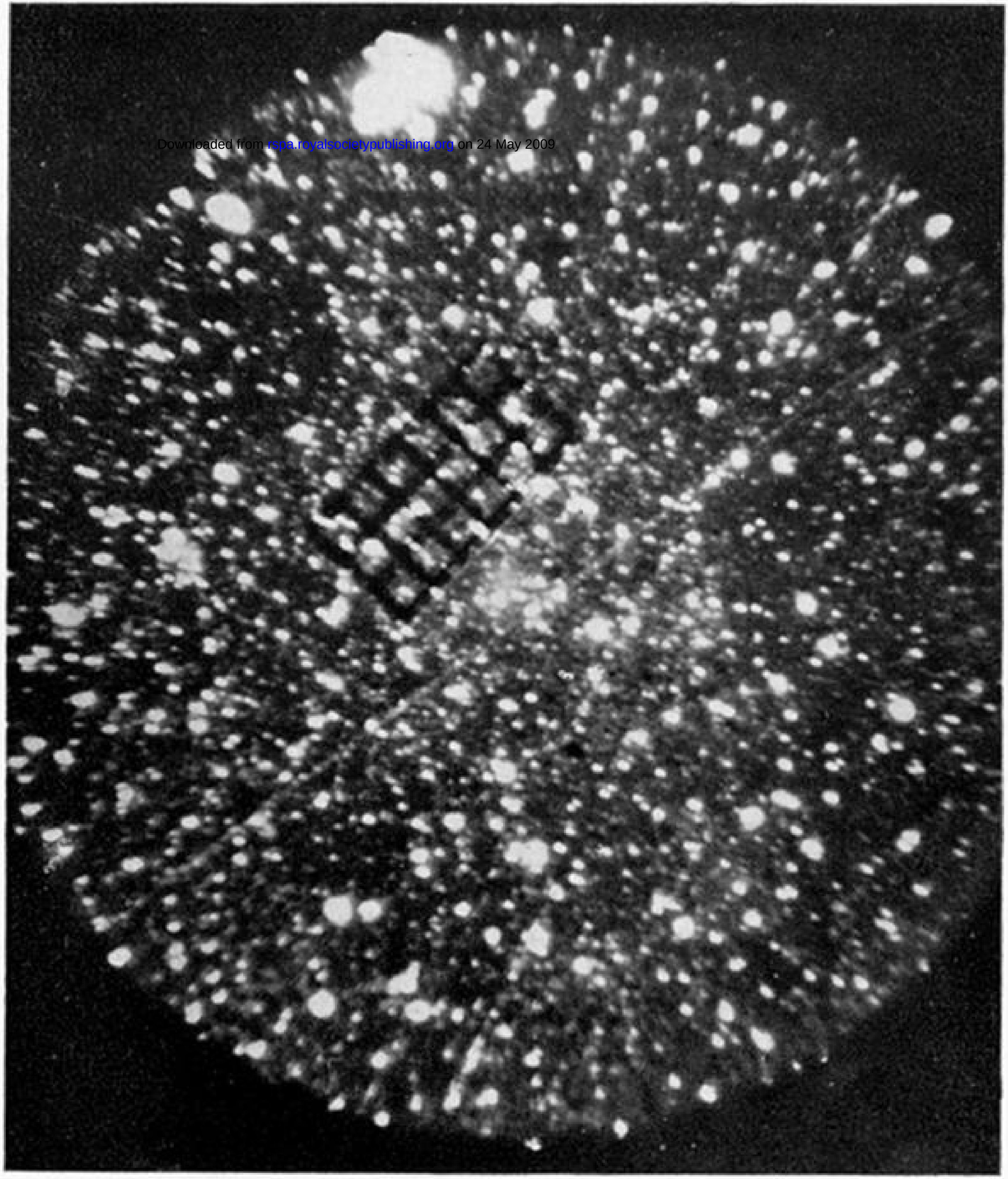

FIG. 3.