Positive Electrons: Focussing of Beams, Measurement of Charge-to-Mass Ratio, Study of Absorption and Conversion into Light

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1. Description of a method ("method of the trochoid") of concentrating and focussing weak electron beams so that they form strong sharp lines on a photographic plate. 2. Displacement of the beam thus formed by an additional field, enabling the observer to recognize the sign of the charge and to estimate the charge-to-mass ratio of the particles, with an accuracy thus far brought up to 15 percent. 3. Absorption, in thin films of platinum and a large number of other elements, of the positive and negative electrons proceeding from a source composed of a radioactive substance emitting strong gamma-rays and enclosed in lead; it is shown that the absorption follows an exponential law over a wide range of thicknesses, and the value of the mass absorption-coefficient is obtained from observations on the imprint made upon a photographic plate behind the absorber. 4. When in the foregoing experiments the thickness of the absorber is increased beyond about 500 mg/cm^2, it becomes evident that the imprint on the plate is partly due to something else than the transmitted electrons. This "something else" is considered to be radiation; with negative electrons it consists entirely of secondary x-rays, with positive electrons there is an additional component ascribed to the merging of positive with negative electrons and their conversion into photons. 5. The absorption-coefficient of these photons implies that their energy is about 0.5 MEV, and the intensity of the radiation implies that there are about two of them per positive electron—two results which agree well with Dirac's theory. 6. Positive electrons have also been observed in conditions where it seems that they proceed directly from radioactive substances.

THE discovery of the positive electron was made by Anderson and confirmed by Blackett and Occhialini, from Wilson-chamber photographs of the tracks of the ionizing particles of the cosmic rays. It was subsequently discovered that gamma-rays have the power of producing these particles when they fall upon matter.[1] However the positive electron is comparatively rare, and all our knowledge of it hitherto has been derived by experiments by the Wilson method. Observations on the curvature of the tracks in a magnetic field, and on the length and the density of ionization of these tracks, have indicated that in charge and mass it is (except for the sign of its charge) much more closely like the negative electron than like the proton or any other known positive particle.

I give here an account of an experimental method particularly suited for forming concentrated beams of charged particles emanating in small numbers from a compact source, and of some results obtained by applying it to positive electrons produced by gamma-rays incident on lead.

THE "METHOD OF THE TROCHOID"

Fig. 1 shows a longitudinal section and Fig. 2 a cross section of the apparatus. The pole-pieces of an electromagnet face each other across a gap, in the center of which the field strength is 10^4 gauss, while in the peripheral parts of the gap it has a considerable radial gradient. In this peripheral region is located the source S (see below); and the charged particles which emerge from S along directions lying close to the plane of Fig. 2 follow "trochoidal" orbits such as are depicted in that figure; and indeed, particles emitted in almost *any* direction in or close to that plane (aperture of almost 2π!) are brought to a narrow region at F, diametrically opposite to S in the peripheral part of the gap. The "yield" of this method of collecting particles

* English version by K. K. Darrow.

[1] Anderson, Science **76**, 238 (1932); Blackett and Occhialini, Proc. Roy. Soc. **A139**, 699 (1933); Anderson and Neddermeyer, Phys. Rev. **43**, 1034 (1933); Curie and Joliot, C.R. **196**, 1581 (1933); Meitner and Philipp, Naturwiss. **24**, 468 (1933); etc. History and references given by Blackett, Nature **132**, 917 (1933); Darrow, Rev. Sci. Inst. **4**, 263, 427 (1933) and **5**, 115 (1934); Scientific Monthly **38**, 1 (1934).

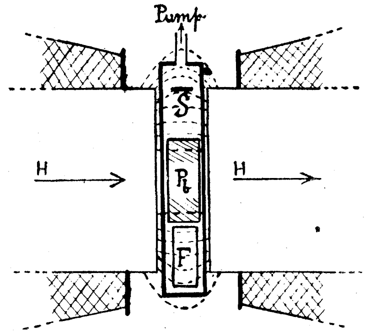

FIG. 1. Longitudinal section of apparatus.

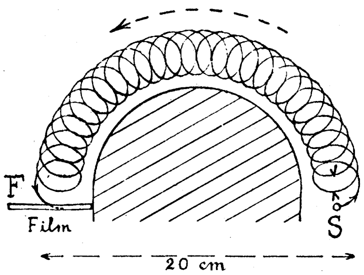

FIG. 2. Cross section of apparatus with diagram of trochoid.

is much (10^2 to 10^3 times) greater than that of any scheme of deflection by a uniform magnetic field.

The source of positive (and negative) electrons is a narrow tube containing some powerful emitter of gamma-rays (radon, salt of radium, or better a salt of RdTh) wrapped in a leaden "radiator" (rolled-up lead foil 0.15 to 0.3 mm thick). The "receiver" F (shielded from the gamma-rays of S by a block of lead 10 to 15 cm thick, Fig. 1) may be a Geiger-Müller counter, an ionization chamber, or a photographic film; I have employed chiefly the last-named. A mere reversal of the direction of the magnetic field brings negative electrons against the film at F instead of positive, or *vice versa*. Either produce on the film *a very compact line* (Fig. 6), *the edge farther from S being especially sharp*, as is brought out by the microphotometer curves (Fig. 3). The lines produced by the two kinds of electrons are identical, if the exposure is 100 to 200 times as long for the positives as for the negatives. The following tests have shown that this line is truly due to the particles which have followed the trochoidal orbits: (*a*) a displacement of S in the plane of Fig. 2 entails a symmetrical displacement of the line; (*b*) the position of the line is (to first approximation) independent of the magnetic field strength; (*c*) the line fades out when S is shifted toward the axis of the system where the magnetic field is uniform; (*d*) films oriented at right angles to H show the expected curves; (*e*) all the particles can be made to pass through a narrow slit in a screen set across the trochoidal orbit of Fig. 2.—Note that the sense of progression of the trochoids in a given magnetic field, and the similarity of the lines produced by the negative electrons and by the new rays, enable us to affirm from the start that the charge-to-mass ratio of the new corpuscle is positive and of the same order as that of the negative electron.

Electrostatic Deflection of Positive Electrons

Two grids are installed at right angles to the "direction of progression" of the trochoids and in front of the photographic film at F (Figs. 2, 4); between them is applied a voltage V and consequently an electric field E, parallel to the said direction and at right angles to the magnetic field H; it produces a radial displacement x of the trajectories and consequently of the line upon the film, x being proportional to E/H and to the time t during which any corpuscle is between the grids. This time-interval t depends on the separation θ between successive turns of the trochoidal orbit, which latter quantity is controlled by the gradient of magnetic field strength in the region where the source and the orbits are, and can be varied at will by varying the distance of S from the axis of the system. The

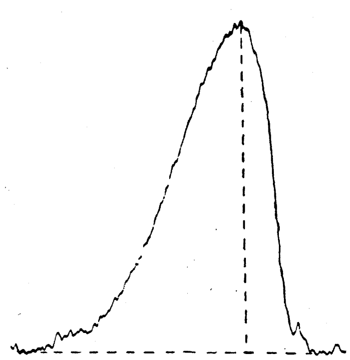

FIG. 3. Microphotometer tracing of the line due to a beam of positive electrons.

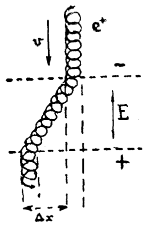

FIG. 4. Displacement of the trochoid by an applied electrostatic field.

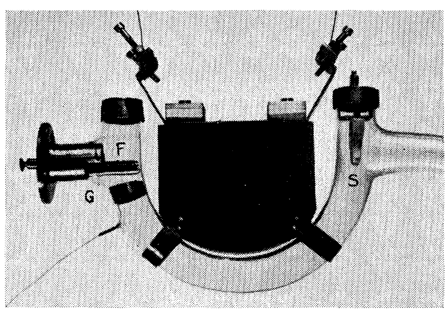

FIG. 5. Photograph of the apparatus prepared for study of positive electrons.

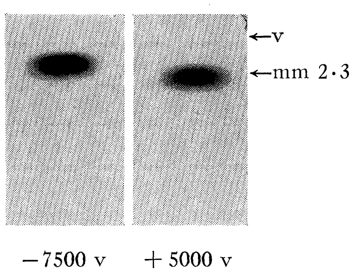

FIG. 6. Line produced on plate by positive electrons, for two values of applied electrostatic field.

first-approximation formulae for θ and x in terms of r the radius of a single turn of the trochoid, ΔH the difference in magnetic field strength at opposite sides of such a turn, and βc the speed of the corpuscles, are the following:

$$\theta = \pi r \Delta H / 2H \tag{1}$$

$$x = 4V/300\beta\Delta H, \tag{2}$$

the units employed being the centimeter, the volt and the gauss.[2]

In the actual experiment, the electromagnet has cylindrical pole-pieces of 20 cm diameter and 3.5 cm gap-width; the electrons travel in a curved tube of Pyrex (Fig. 5); S is seen at the right, F at the left; the two grids G are parallel to the film and 1 cm apart. When the voltage is applied between the grids, the line due to the electrons impinging on the film is displaced by about 1 mm for each 5000 volts; Fig. 6, relating to positive electrons, exhibits the displacement of 2.3 mm due to a change in the voltage from +5000 to −7500. When the magnetic field is reversed, negative electrons instead of positives come to the film, and the displacement produced by the application of the voltage is reversed in sign.

MEASUREMENT OF e/m FOR POSITIVE ELECTRONS

Combining Eq. (2) with the following equation,

$$Hr = (m_0c^2/e)\beta/(1-\beta^2)^{\frac{1}{2}} \tag{3}$$

one sees that it is possible to evaluate e/m and β if r and the values of magnetic field strength at all points of the trochoidal orbits are known. The field strengths are determined by placing a little block of nickel of known susceptibility, suspended from a balance, at various points of the gap; r is determined by photographing the electron tracks. Unfortunately the positive electrons have a distribution-in-energy extending over a wide range, the most probable energy values lying between 800 and 900 electron kilovolts; the measured value of r is only a mean value; the best that can be concluded from this "absolute" determination of e/m_0 for positive electrons is that it is between one-half and twice the value for negative electrons. A more accurate "relative" determination can be made by comparing the values of x observed with positive and negative electrons. A more accurate "relative" determination can be made by comparing the values of x observed with positive and negative electrons. On plotting them against voltage, the two straight lines of Fig. 7 were obtained; their slopes are equal within the uncertainty of experiment, so also must be[3] the products $(m_0/e)\beta^2/(1-\beta^2)^{\frac{1}{2}}$; and comparing the mean radii r of the turns of the trochoids made by the electrons

[2] It has been shown by L. Cartan (C.R. **197**, 1604 (1933)) that the substitution of relativistic for classical mechanics does not impair these formulae.

[3] In expression (2) for the displacement x, ΔH is proportional to the gradient of the magnetic field and to the radius r of the orbit. Thus x will vary inversely as βr, and hence, according to expression (3), inversely as $(m_0/e)\beta^2/(1-\beta^2)^{\frac{1}{2}}$.

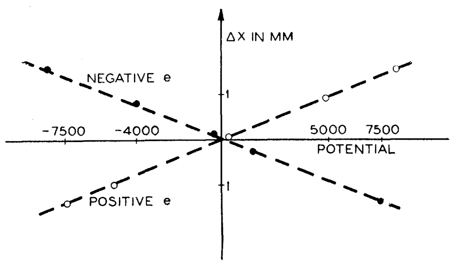

FIG. 7. Illustrating the determination of e/m.

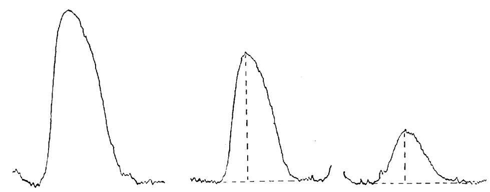

FIG. 7A. Microphotometer tracing of the lines due to the same beam of positive electrons after passage through different thicknesses of absorber.

of the two signs, I conclude that the charge-to-mass ratio of the positive electron cannot differ by more than 15 percent from that of the negative electron.

PASSAGE OF POSITIVE ELECTRONS THROUGH MATTER: SCATTERING AND ABSORPTION

The method of the trochoid, combined with a photometric study of the imprint made upon the photographic film (we employ the registering microphometer of Chalonge and Lambert) is well suited for investigating the "absorption" of electrons in matter. The law of the photographic action is the same for positive as for negative electrons,[4] and it has been verified that the density S of the spot is proportional to the number of incident positives all the way up to $S=1$. Fig. 7A exhibits three photometer curves, obtained with three thicknesses of absorbing matter (the absorbing screens are pressed closely against the film): it is seen that the general aspect of the line (especially its dissymmetry) remains the same.

For each of the elements studied, we have plotted the logarithm of the transmitted intensity (or photographic density) against the mass-per-unit-area of the absorbing screens (Fig. 9 shows an example for platinum). In general, the curves are concave toward the axis of abscissae from $x=0$ onward to about $x=50$ mg/cm^2; thenceforward they are linear over a considerable interval (though not indefinitely!), and we may define and measure a "mass-absorption-coefficient" μ/ρ in the customary fashion. For a long list of elements (C, Al, S, Ca, Mn, Ni, Cu, Zn, As, Se, Mo, Pd, Ag, Cd, Sn, Ce, Ta, Pt, Au, Pb) and for the particular distribution of positive electrons emanating from our source (RdTh), the values of μ/ρ lie between 8 and 10; the differences are probably due in part to errors of measurement,[4] but in part to a periodic variation of μ/ρ with atomic number Z. The negative electrons proceeding from the same source (expelled by the thorium gamma-rays from the atoms of the radioactive substances and of the enclosing lead foil) likewise have an absorption-curve which, when plotted in this semi-logarithmic fashion, exhibits a long straight portion;[5] the example in Fig. 9 (lower curve) yields a value 13.7 for μ/ρ.

The absorption of the positive electrons in air was studied by introducing air at various pressures into the apparatus, measuring the corresponding densities of the spot, and adopting for the total length L of the trochoid the formula $L=4\pi RH/\Delta H$, where R stands for the distance to the source from the axis of the system (Fig. 2). The semi-logarithmic curve is shown in Fig. 8;

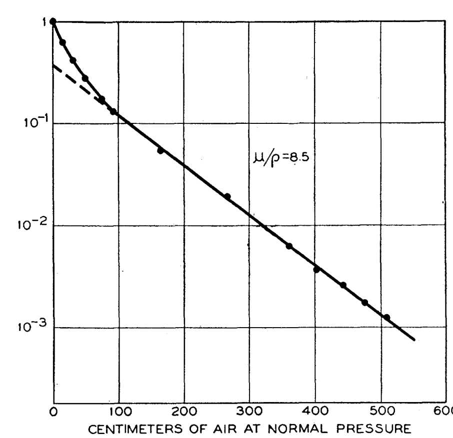

FIG. 8. Absorption-curve of positive electrons in air.

[4] Thibaud and Dupré la Tour, C.R. **198**, 805 (1934).

[5] It has long been known that inhomogeneous electron beams, such as ours is, may exhibit an exponential absorption law (which on the semi-logarithmic plot appears as a linear law). Cf. for instance K. W. F. Kohlrausch, *Radioaktivität*, p. 367 (Handbuch der Physik).

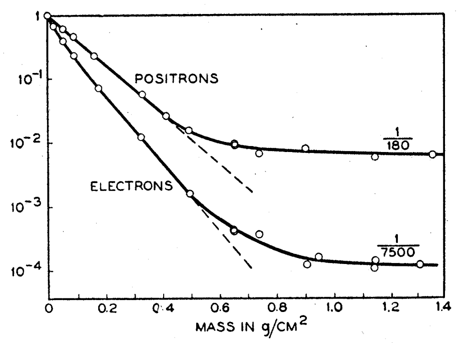

FIG. 9. Absorption-curves of positive and negative electrons in platinum, with extension attributed to photons.

it is convex[6] for low values of x, subsequently straight; the value of μ/ρ is 8.5, in good agreement with those obtained with solid absorbers.

Our general conclusion is, that as they pass through matter up to thicknesses of the order of at least 500 mg/cm^2, these positive electrons behave like negatives, undergoing a similar scattering and slowing-down by virtue of their interactions with atomic electrons and nuclei.[7] But as the thickness of the screens is further increased, a different phenomenon comes to notice.

Radiation Ascribed to Stopping and to Annihilation of Positive Electrons

Returning to Fig. 9, it is seen that the sensibly-straight portion of each of the absorption curves is succeeded by a portion with a notable upward concavity, which approaches a not-quite-horizontal asymptote. This signifies that the effect produced on the film by *photons excited within the metal by the electrons* is becoming comparable with that produced by the electrons which succeed in traversing the whole of the metal and reaching the film. In the case of *negative* electrons, all of these photons are presumed to belong to the well-known x-ray spectrum (both line-spectrum and continuum) evoked whenever fast electrons impinge on matter. Their contribution to the blackening of the film is actually very slight, only 1/7500 of the effect of the primary beam when no absorber is interposed. This is not surprising in view of the small yield (a few percent) of x-ray emission from platinum evoked by electrons of these speeds. On comparing the two curves of Fig. 9 one sees, however, that the photons produced by the *positive* electrons have a much greater effect. Beyond 500 mg/cm^2 of Pt (at which thickness more than 1 percent of the incident positives are still transmitted) there is evident an intense and penetrating radiation. Its limiting strength produces a blackening 1/180 of that caused by the undiminished primary beam and some *fifty times* as great as that due to the photons evoked by negative electrons. (The difference is also made obvious by the fact that at 100 mg/cm^2 the film must be exposed 200 times as long to the positives as to the negatives to get the same blackening, while at 1000 mg/cm^2 the ratio of exposures is only 4.) Meanwhile, the aspect of the spot on the film is changing; the original fairly sharp "line" of Fig. 3 is replaced by a much broadened area with no definite edge nor sharply-marked central maximum of blackness. We infer that the imprint of the transmitted fraction of the beam of positives is masked by a secondary radiation (photons) emitted in all directions.

The mean frequency of the new radiation can be deduced from the slope of the not-quite-horizontal asymptote of Fig. 9. Most of the photons are presumably produced near the front surface of the absorbing metal,[8] while the major part of their photographic effect is presumably due to secondary electrons produced near the rear surface and springing out of the metal against the film. We therefore kept the rear surface of the metal pressed against the film,

[6] Thibaud, C.R. **198**, 562 (1934). Curves of this shape have been obtained by Crowther with negative electrons (Proc. Roy. Soc. **A80**, 186 (1908)).

[7] Note that the trochoidal trajectories enter the solid absorbing screens almost tangentially, but, owing to the scattering of the positives which commences as soon as they enter the screens, it is proper to assume that the thickness of these screens corresponds to the real path of the corpuscles in metal. This assumption is supported by the identity of the values of μ/ρ obtained with solids and with air.

[8] This is due to the very strong diffusion of the electrons which occurs shortly after they enter the metal; one can thus find, at a very small distance ϵ from the front surface of the metal, corpuscles which have already traversed in the metal a distance L much greater than ϵ and are close to the ends of their courses and to their ultimate annihilation. Our measurements show that in platinum half of the positive electrons have already been diffused laterally at a depth of 0.0035 cm. With the thickness of 0.05 cm or more corresponding to an areal density of 1000 mg/cm^2, very few electrons will traverse the metal undeflected. The "centroid of emission" of the photons will thus be very close to the surface.

but maintained a constant value of the distance from the film to the front surface; these apparently contradictory requirements were fulfilled by separating, to a greater or less extent, the several sheets constituting the various thicknesses of absorber. It is possible to compute, by use of King's functions, what fraction of the total energy radiated in all directions in the form of photons is absorbed in such a manner as to produce secondary electrons which attain the film; the fraction comes out to about 0.05.

Experiments conducted in this manner, with thicknesses of absorber extending up to 1700 mg/cm^2, indicate a value of 0.2 for the mass-absorption-coefficient of the photons. This result is confirmed by a direct count of the transmitted photons with a Geiger counter in place of the film (the gamma-rays from the radioactive substances in the source cause much trouble in this case). This value of mass-absorption-coefficient suggests photons of energy about 0.5 MEV. The energy of the x-ray photons produced by the negative electrons is sufficiently near to the foregoing value, to justify us in assuming that the photographic effect per photon is about the same for both types of radiation, and hence that the positive electrons produce about 50 times as many photons altogether as the negatives.

From our general knowledge of the efficiency of production of x-rays by electrons of various energies impinging on various anticathodes, it is possible to make a rough estimate of the number of x-ray photons which the negative electrons of these experiments, with their energies distributed about a mean value of some 0.4 MEV, would be expected to produce in the various absorbers.[9] In the case of platinum it comes out to about 0.04 photons per electron. Multiplying this by 50, we obtain about *two photons per positive electron* as our estimate of the "yield" of the additional process peculiar to positive electrons. To make a closer evaluation it will be necessary to know more accurately the distribution-in-energy of the negative electrons.

It is clear that our two major conclusions—that the energy of these photons is about 0.5 MEV, that the number thereof is about twice the number of the positive electrons—are both compatible with the theory that *these photons arise through the fusion of a positive with a negative electron* (the latter presumably one of those already present in the metal) *every such process producing two photons which share the energy derived from the rest-masses of the electrons.* For if two electrons of opposite sign encounter one another while moving with negligible speeds, and merge and are converted into radiation, then two identical photons must spring off in opposite directions in order to assure conservation of momentum, and each of these must have one-half of the energy originally manifested as the rest-masses of the two electrons, which is to say, one-half of 1.02 MEV. "Negligible speeds" in the foregoing sentence signifies speeds for which the kinetic energy is very small compared with 0.5 MEV; it seems reasonable to suppose that positive electrons and negative electrons are especially likely to combine, when their speeds are small in this sense.

This accordingly appears to be the strongest evidence thus far obtained for *the process of the conversion of electricity*—we may say, *the conversion of matter—into radiation*, often suggested of recent years, and vital to many cosmogonic theories.[10] This is the opposite of the process of conversion of light into electricity, first postu-

[9] These electrons have a continuous spectrum extending beyond 2 MEV, in addition to spectrum-lines of photoelectric origin. The "practical average speed" prevailing after the electrons have traversed the thin surface-layer of the platinum is ascertained from the previously-cited absorption coefficient ($\mu/\rho = 13.7$); we estimate what would be the corresponding coefficient for Al, and then take the corresponding electron-speed from tables of Lenard; it appears that β is a little less than 0.85, the energy therefore about 0.4 MEV. We compute the yield of radiant energy from the expression CZU, putting 78 for Z the atomic number (of Pt) and 0.4 MEV for U the energy of the electrons and 10^{-6} for the constant C; and divide this by an estimated average energy of the photons. This calculation is justified by the results of the measurements of J. A. Gray (Phys. Rev. **25**, 237 (1925)) on the x-ray emission caused by the beta-ray spectra of radioactive substances. We ignore the effect of the $K\alpha$ line of Pt, reduced by absorption to a few percent.

[10] Gray and Tarrant and several others have observed radiation proceeding from metals irradiated by gamma-rays, which they attribute to this process; the positive electrons involved in the process are supposed to be created out of the gamma-ray photons (along with negative electrons) within the metal itself.—Joliot also observed, with the method of the trochoid, radiation of this character springing from metals bombarded by positive electrons (C.R. **197**, 1622 (1933)); he employed a Geiger counter for detection, and a considerable part (86 percent) of the observed radiation seems to have been due to parasitic effects, perhaps the contamination of the laboratory (see my criticism, C.R. **198**, 562 (1934)); the photographic method is exempt from this source of uncertainty.

lated by Dirac, which is supposed to be occurring in many cases where positive electrons are observed—*e.g.*, in the cases where gamma-rays impinge on heavy metals and positive electrons spring forth.[11] However, the process commonly postulated in the latter case is not the exact converse of the one which we postulate to explain the experiments here described. In our experiments it seems that *two* electrons merge to produce *two* equal photons, whereas in the other case it seems that a *single* photon produces two electrons. The conversion of one photon into two electrons would not be compatible with the conservation of momentum, unless the process were to occur in the vicinity of an atom-nucleus which could take up a certain amount of momentum; it is generally assumed that this happens. It therefore appears (from the experiments thus far recorded in the literature) that the conversion of photons into electrons occurs chiefly under conditions where atom-nuclei participate in the process, while the conversion of electrons into photons occurs chiefly as a self-contained process not involving the participation of nuclei.[12]

"Free Path Before Conversion" of Positive Electrons

The positive electron is distinguished from its negative counterpart by its very short "mean life," curtailed by its eventual conversion into light. We point out that this distinction may not be fundamental at all, but simply a result of the vast excess of negative electrons in the universe which we know. Were the orbital electrons of atoms positive instead of negative, it would probably be the negative electron which would have the short life.

From the curves of Fig. 9 we infer that the free path before conversion of a positive electron in platinum is at least 0.03 cm, corresponding to a stratum of metal of areal density 600 mg/cm^2; while our experiments with air suggest a free path corresponding to 640 mg/cm^2 (at least 500 cm of air at N.T.P.). These two figures are so nearly alike as to imply that interactions with negative electrons are responsible both for the slowing-down and for the eventual conversion of positive electrons.

Positive Electrons from Radioactive Substances

We have found that a thin-walled glass tube of radon emits more positive electrons than proceed from a source formed by enclosing the same tube in lead;[13] a like result has been obtained with a tube of RdTh. It is unlikely that the wall of glass, thin as it is and consisting of light elements, should be responsible for this emission. We attribute it to processes occurring in the radioactive substance itself—perhaps conversion of gamma-rays into electrons, perhaps impacts of alpha-particles against nuclei.

Some years ago I observed[14] gamma-ray photons of energy 0.507 MEV proceeding from the two substances Ra C and Th C″—that is to say, the two substances of which the gamma-ray spectrum extends well beyond one MEV. It is not too unplausible to suggest that these gamma-rays may be due to the conversion into light of "natural" positive electrons, emitted by the radioactive substance itself and converted before they escape.

[11] See references given at end of footnote 1; also Oppenheimer and Plesset, Phys. Rev. **44**, 53–55 (1933).

[12] This idea is supported by the observations of Gray and Tarrant, who found in their experiments that 0.5-MEV photons were much more abundant than 1-MEV photons (footnote 10).

[13] Thibaud, C.R. **197**, 915 (1933).

[14] J. Thibaud, Thesis, Paris, 1925; see C.R. **198**, 562 (1933).

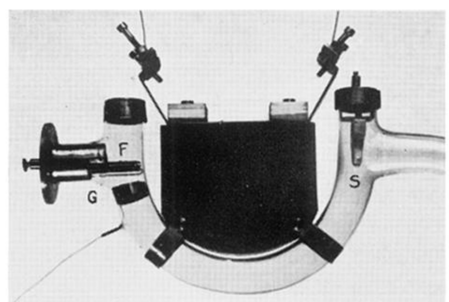

FIG. 5. Photograph of the apparatus prepared for study of positive electrons.

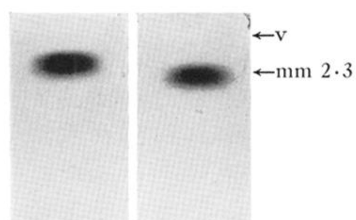

FIG. 6. Line produced on plate by positive electrons, for two values of applied electrostatic field.