It is surprising that the assumption that all scattered quanta of one group have the same energy yields results so closely in agreement with experiments on both intensity and spectral distribution of the radiation. The meaning of this assumption in terms of the energy distribution is illustrated in Fig. 7, in which the number of quanta with energy greater than E has been plotted. This number increases by N whenever E passes through one of the energies E_k. The same number has been computed from a statistical study of 200 calculated γ-ray tracks by Dr. Fano and Mr. Karr[8] at the National Bureau of Standards and is also shown in Fig. 7. The similarity of the two curves accounts for the close agreement between our experimental and calculated results.

[8] We are indebted to Dr. Fano and Mr. Karr for permission to quote the results of their work on an Office of Naval Research contract.

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Conductivity Induced by Electron Bombardment in Thin Insulating Films

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When thin films of insulating material are bombarded by high velocity electron beams that can penetrate through the thickness of the film, steady currents can be obtained that are as much as 100 times that in the bombarding beam. These currents vary with the gradient across the film and are proportional to the fraction of the beam energy absorbed in the film. Typical data obtained with amorphous silica are presented, together with a description of the experimental procedures that were used.

INTRODUCTION

ALTHOUGH considerable work has been done with the bombardment of insulators by electron beams, most of it has been related to emission of secondary electrons. Relatively few papers have dealt with the problem of the currents induced by the bombarding beam, even though this has been known for some time,[1] and most of these dealt with semiconducting and photo-conductive materials.[2–4] More recently some work has been done with crystals of silver chloride and diamond, as reported by Van Heerden.[5] In these cases pulses of current were observed to flow through the crystal under bombardment by pulses of ionizing particles like alpha-particles[6] or pulsed electron beams.[7] The magnitudes of these currents are very sensitive to the structure of the crystal.

An effect has been found, however, which is not dependent on the crystalline structure and has been found in all of the several insulating films tried to date. Among these are silica, magnesium fluoride, electrolytic aluminum oxide, and mica. It was found that electrons can flow continuously through thin films of the insulator when bombarded by an electron beam of sufficient velocity to penetrate through the thickness of the film. These currents have been observed to be as large as 100 times that of the bombarding beam and are proportional to the energy absorbed from the bombarding beam.

[1] A. Becker, Ann. d. Physik **13**, 394 (1904).
[2] R. Kronig, Phys. Rev. **24**, 377 (1924).
[3] R. Frerichs, Phys. Rev. **72**, 594 (1947).
[4] E. S. Rittner, Phys. Rev. **73**, 1212 (1948).
[5] P. J. Van Heerden, *The Crystal Counter* (N. V. Noord-Hollandsche Uitgevers Maatschappij, Amsterdam, 1945).
[6] A. J. Hearn, Phys. Rev. **23**, 524 (1948).
[7] K. G. McKay, Phys. Rev. **74**, 1606 (1948).

EXPERIMENTAL PROCEDURE

The tests described below refer to thin films of amorphous silica on Nichrome base metal plates two inches square. The films were in the range of thickness from 2500A to 15,000A and were prepared by heating the plates in an atmosphere of ethyl silicate vapor, which decomposes at high temperature to form silica. This process* was chosen for the tests because it provided films that were much better insulators than could be obtained by the evaporation of fused quartz from tungsten filaments. Other insulating films, such as aluminum oxide, magnesium fluoride, and barium borate were tried as examples of readily available materials and were found to show the effect of bombardment induced conduction, but no comparable data has as yet been taken.

In order to perform the measurements, the targets were set up in an evacuated envelope which was equipped with two cathode-ray guns, so spaced as to permit the deflection of the beams by standard television deflection yokes, as shown in Fig. 1. The target was connected to a video amplifier which ultimately drove the grid of a standard kinescope whose deflection yoke was driven in synchronism with those of the test tube. The decoupling filter shown in the Fig. 1 was designed to permit the application of d.c. voltages to the target plates. The meter marked "microampere No. 1" reads only the current striking the target and meter marked "microampere No. 2" reads only the current that passed through the insulating film to the base metal. Some care was taken with close-fitting mica shields to prevent electrons from reaching the base metal by any path other than through the film.

When one of the cathode-ray guns is turned on at comparatively low voltage (600 to 1000 volts), there is no appreciable penetration through the film, and the operation is as one would expect from the well-known phenomena characterizing the behavior of insulators under an electron bombardment. Because the secondary emission ratio is greater than unity, the surface is held at approximately the potential of the collector, which in this case is the wall coating. This potential is independent of that applied to the base metal, which can now be adjusted to provide a predetermined potential drop across the film. Any charges that leak through the film will also be removed by the scanning beam. In addition, the beam generates a television-type signal as it scans over the surface by a mechanism similar to that in the iconoscope.[8] This signal, when viewed in the kinescope, produces a uniform picture when the surface is at equilibrium. However, any deviation from that potential, for any reason, shows up as a light or dark area. This provides a two-dimensional check on the surface potential.

Under such conditions the data of Fig. 2 were obtained. The target metal potential was set with respect to the collector at the values shown on the figure, and the beam current was varied. Some small leakage currents were found which varied directly with the beam current and were found to be relatively independent of the beam voltage over the range of 500 to 800 volts. The crossing of two of the lines is assumed to be an artifact because of the difficulty of obtaining reproducible measurements with the small currents involved.

Figure 3 shows how the leakage current varied with target voltage, keeping the beam current and beam voltage fixed. For the range of data shown the current is an exponential function of the target voltage. The dashed portion of the

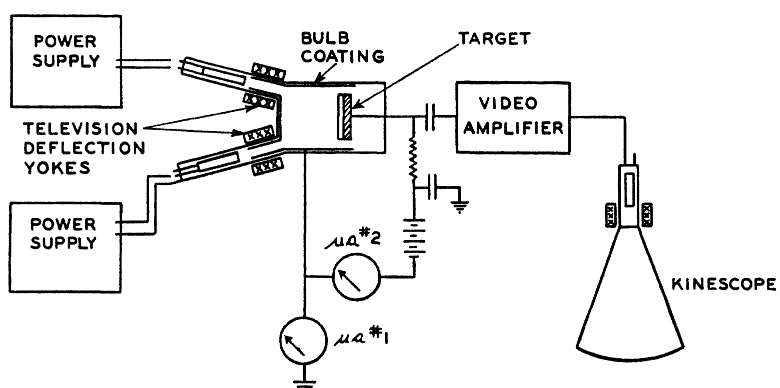

FIG. 1. Arrangement of apparatus.

* Developed by H. B. Law of the RCA Laboratories Division.
[8] Zworykin, Morton, and Flory, Proc. I.R.E. 25, 1071 (1937).

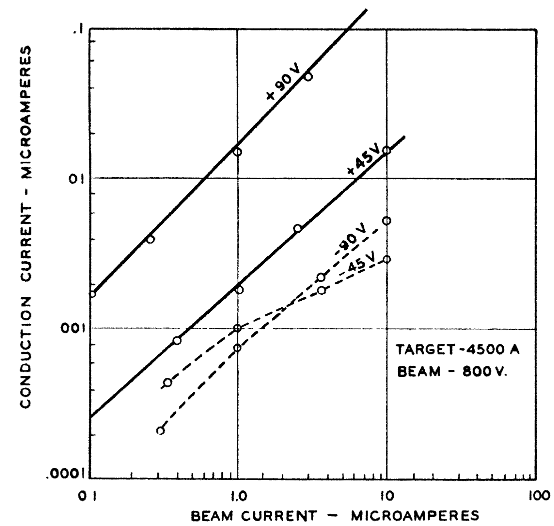

FIG. 2. Conduction current as a function of beam current.

curve is extrapolated to indicate an expected approach to zero current at zero target voltage.

A possible explanation of these small currents is that there are flaws in the film through which base metal shows and that secondary emission can be obtained from it when it is negative. Because the percentage area involved is small, the observed currents would be small. When the metal is positive the bare areas can act as collectors of redistributed secondary electrons that originate in the insulator, and in this case the current can be appreciably larger than with the negative voltage. The exponential character, however, is not explained. This effect was not further investigated because it was of less interest than the larger order effect described below.

An interesting phenomenon was observed in attempting to take measurements with negative target voltage appreciably greater than those indicated. As the gradient exceeded 2×10^6 volts per centimeter, occasional sparking was observed in the kinescope as a burst of electrons emanating from a point and spraying over the region around it, causing this region of the surface to become highly negative until it was again charged up by the beam.

Figure 4 shows the beginnings of the increased conduction resulting from the increasing penetration by the beam. The curves are similar to those of Fig. 2, except that the film is only 2500A thick. Increasing the beam voltage now shows an increased conduction current through the film. It is readily apparent, however, that as the conduction current approaches an appreciable fraction of the beam current the surface potential begins to drift towards the base metal potential. This is more obvious in the case where the film approaches a good conductor. The loss of surface potential sets a limit to measurements of this type with high velocity beams.

For this reason a two-beam technique was devised that permitted extending the range of

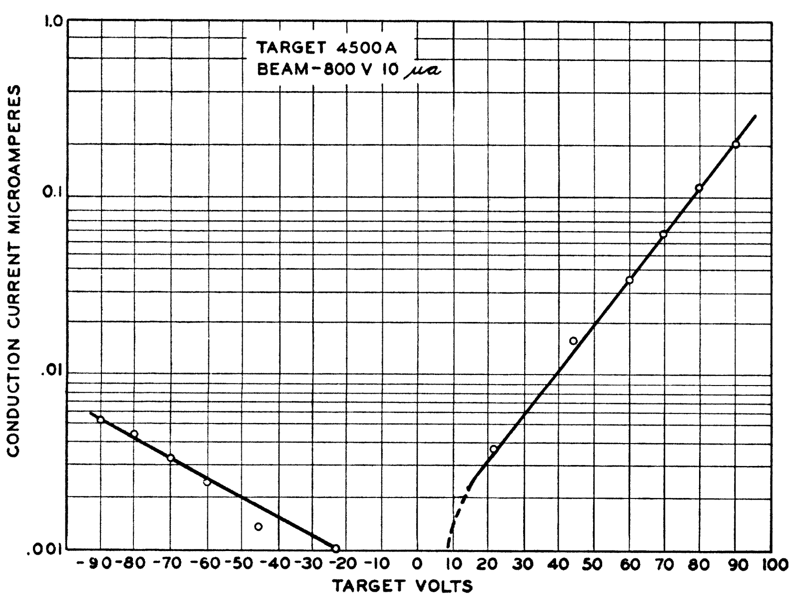

FIG. 3. Conduction current as a function of target voltage.

measurements in the following manner. The one beam was set at a fixed voltage low enough so that the conduction effect due to it was suitably small. The current in this beam was made large enough to be well in excess of any conduction currents that might be generated by the second beam whose voltage was varied over the desired range. The currents in this second beam were held to a small enough value so that its conduction effects would not require going beyond the practical limits for the first gun. Typical values that illustrate this principle are:

	Volts	Current	Cond. current
Beam 1	800	10 ua	0.1 ua
Beam 2	10,000	0.02 ua	1.0 ua

It is apparent that the low voltage beam current was well in excess of the total conduction current through the film, and so the surface potential was held at collector potential. For this reason the potential drop across the film was still known and controlable.

For purposes of describing the experimental data without reference to specific currents, the term "conduction ratio" was applied to the ratio of the conduction currents to the beam current that excited it. For example, the conduction ratio of the beam 2 above would be 50.

Figure 5 shows a typical set of data as the voltage of the second beam was varied. The solid line curves are for the positive voltages applied to the base metal, and the dashed lines are for negative voltages. It is apparent that the conduction ratio rises very rapidly with increasing voltage at the lower beam voltages, reaching a maximum and then tapering off slowly. Increasing the potential drop across the film increased the conduction ratio at any given voltage. The ratio was also larger for positive voltages, which is the direction of gradient such as to pass electrons from the bombarded surface through the film to the base metal.

Figure 6 shows the effect with different thicknesses of film. The curves are marked with the thickness in angstrom units, and for each film a positive gradient was set at the value of 10^6 volts per centimeter. The second beam voltage was varied as above. Although these curves are rather flat, some rough conclusions can be drawn. First it is to be noted that the voltage at the maximum

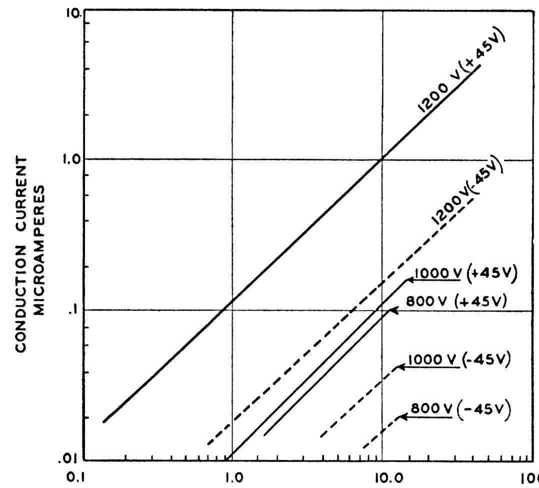

FIG. 4. Increased conduction due to the increasing penetrating of the beam.

increases with film thickness. In particular, this voltage increases approximately with the square root of film thickness, as would be expected from the Thomson-Whiddington law. Secondly, the increasing conduction ratios at the maxima indicate an increased conduction effect with increased film thickness. Again as a rough approximation, the magnitude of the increase is proportional to the voltage at the maximum. For example, the 2500A film can be said to have a maximum conduction ratio of 9 at a beam voltage of 6 kv. The 9000A curve shows a maximum at

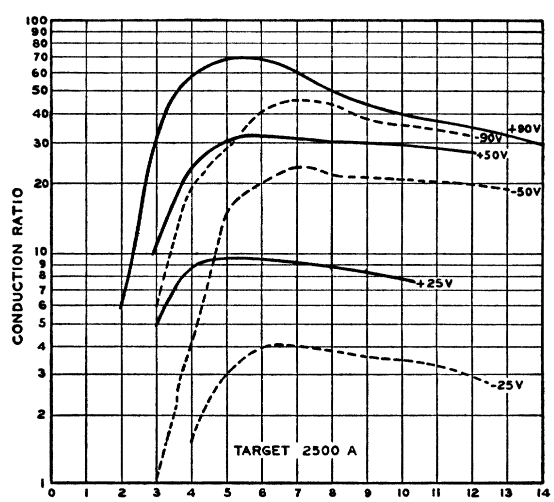

FIG. 5. Typical data with the two-beam technique.

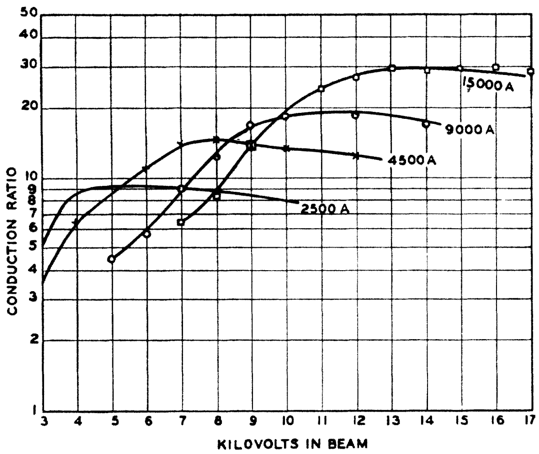

FIG. 6. Effects of varying the film thickness.

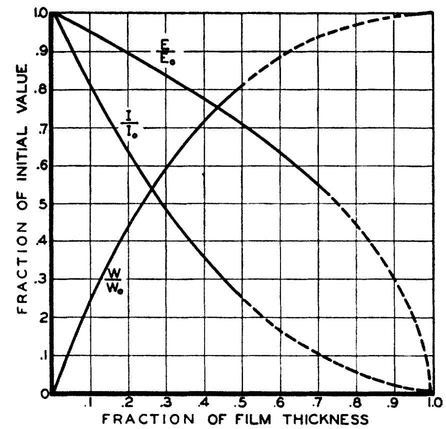

FIG. 7. Power losses in thin film.

12 kv, which is double the previous voltage, and the conduction ratio is approximately 19, which is slightly over double that of the thinner film. This appears to indicate that the conduction effect is proportional to the beam energy absorbed in the film.

The indication of the proportionality of the effect with absorbed beam energy can be supported by a different consideration. We can calculate the energy losses in a thin film by a beam of electrons as the beam velocity exceeds that required for penetration. The Thomson-Whiddington law indicates that the range of electrons goes up with the square of the voltage. Experimental data of Terrill[9] indicate that the current in a beam falls off exponentially with depth of penetration. Both these laws were transposed to the form shown in Fig. 7, which assumes a film thickness of unity and an electron beam velocity just able to penetrate it. The latter is obtained from the Thomson-Whiddington law which defines the range or the maximum depth of penetration by extrapolating the initial loss of voltage on penetration into the material. The falling off of current and voltage are plotted as fractions of the initial value against the fraction of the film thickness penetrated. The dashed portions of the curves indicate the regions where experimental data have not been available to verify the laws involved. Based on these two curves, a third curve was obtained which is the product of the loss of current and loss of voltage and is therefore the loss of power with penetration into the film. This indicates the interesting fact that 80 percent of the power is lost in the first half of the range of penetration.

It is a relatively simple matter to compute from this power curve what the energy loss is as a function of beam voltage for a given film thickness, as the voltage is increased to values above that required for penetration. The solid line of Fig. 8 is such a curve for one of the thicknesses used. In this case the range voltage is 6.3 kv, so that for all lower values all of the beam energy is absorbed. This part of the curve is therefore a straight line with a 45° slope. The line starts to curve when the voltage begins to exceed that for which the range is the film thickness, but the total energy absorbed continues to rise with voltage because the energy loss occurs primarily in the first half of the range. The absorbed energy decreases at still higher voltages because the range increases with the square of the voltage so that the fraction of the beam energy absorbed begins to decrease faster than the increase in the initial energy.

The experimental data for this film were plotted as dashed lines, using an arbitrary scale chosen only for purposes of comparing curve shapes. We find once more that the broad maxima prevent an accurate matching, but the similarity is very suggestive.

The locations of the maxima in the experimental and calculated curves are close enough to be within experimental error, whereby a further check is provided on the theory of penetra-

[9] H. M. Terrill, Phys. Rev. 24, 616 (1924).

tion. Also, the similarity of slopes after the maxima points to the proportionality of the effect with absorbed energy. This relationship would then appear to be substantiated by the measurements on a single film as well as by the comparison of a range of thicknesses. The differences occur primarily in the low voltage region where the unknown factor of incomplete penetration would be expected to cause a reduction of the conduction effect.

CONCLUSIONS

The excitation of conduction current by a penetrating electron beam has been found in all insulating materials tested. This indicates that the effect is not critically dependent on the crystal structure of the material. It is, therefore, possible to obtain an elementary picture of the phenomenon based primarily on the fact that almost all of the energy of a high speed electron on penetrating into a solid body is given up to the bound electrons by collision processes. These bound electrons are thereby made free to migrate in the direction of an applied gradient. If it is assumed that the energy required to free a bound electron is of the order of 10 to 20 electron volts, then a 10,000-volt primary electron should excite from 500 to 1000 low velocity electrons. These electrons are subject to trapping by several mechanisms, including that of capture by the positive ions that were also generated. It is not likely that the steady state current observed means that any electrons have gone through the entire thickness of the film. It is more reasonable to assume that the electrons freed near the front surface go part way into the interior and then become trapped, thus building up a space charge. If the beam penetrates beyond this point, the electrons freed in the interior leave positive ions that reduce the space charge. There is thus a progressive travel of current as a series of jumps of electrons along the path of the penetrating beam. If penetration is complete, then a steady current can be observed. Otherwise, on incomplete penetration, the build-up space charge rapidly reduces the current to those low values which represent that fraction of the excited electrons that can escape the traps and migrate through the unpenetrated region. This fraction falls off rapidly with increasing length of unpenetrated path. The experimental data in the voltage range below that of the maximum conduction ratio (see Fig. 8) indicates a rapid falling off of the conduction effect with decreasing voltage where penetration is incomplete. This picture of the process also indicates why the effect falls off with increasing voltage after the maximum. The total number of electrons excited is proportional to the absorbed energy, and the current through the film should be proportional to the number of excited electrons.

When the base metal is negative, it is possible

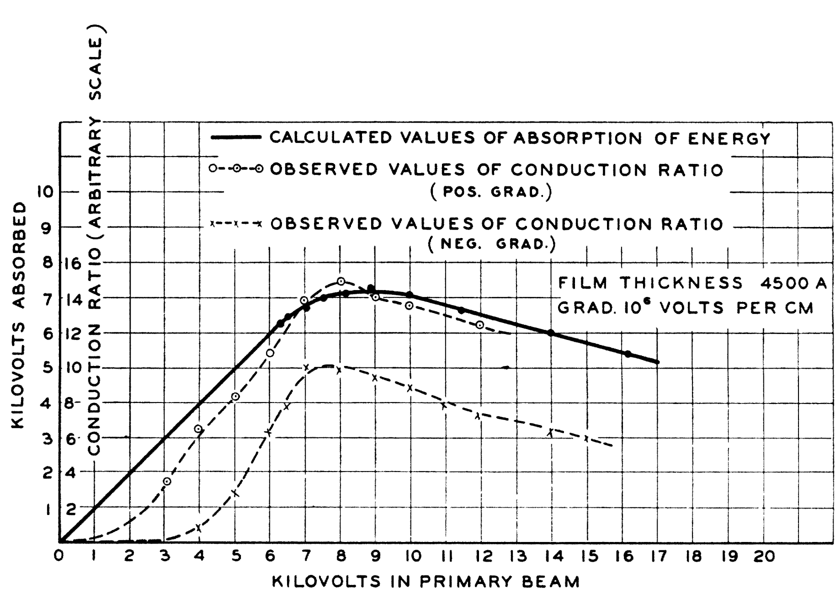

FIG. 8. Energy loss as a function of voltage.

to assume a similar process, but dealing with the travel of holes instead of electrons. Because the mobility of holes is appreciably less than that of electrons, there should be observed a more rapid decrease of conduction current with decreasing penetration. This too is supported by the curve for negative gradient in Fig. 8. The recovery of full insulation after removal of the penetrating beam, with both types of conduction, is to be expected. No current should flow on the mere application of a gradient without a means of exciting the electrons in the interior.

This simple theory leaves unexplained, however, the observation in the data of Fig. 6, that the conduction ratio is proportional to the beam voltage at the maximum regardless of the film thickness. It is to be expected that, on doubling the beam voltage, the number of excited electrons is doubled, but the path length is increased four times. If the range of excited electrons is constant, the increased path length should result in a decrease of current in spite of the increased number of excited electrons in the thicker film. The fact is that current increases, and in an amount that indicates no appreciable loss due to the increased film thickness.

SUMMARY

An apparently new type of conduction effect has been found which occurs on fairly complete penetration through an insulator film and seems to be present in an uncritical manner in each of several insulator materials tried. The conduction currents can exceed the penetrating beam current by many times, and the insulation recovers completely after the penetrating beam is removed. The effect is shown to be proportional to the amount of beam energy absorbed.

ACKNOWLEDGMENT

The author wishes to express his appreciation of the value of many profitable discussions with Dr. A. Rose and of the encouragement and support by Dr. L. E. Flory.

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The Recording of Electron Tracks in Photographic Emulsions*

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Four different methods of obtaining electron tracks in nuclear-track plates are described. Electron tracks have been produced by x-rays, by natural radioactive decay, by exposures in an electron microscope, and by feeble, induced radioactivity. A first attempt at establishing the range-energy relationship of electrons has been made from length measurements of electron tracks produced by heterogeneous and monochromatic x-rays at various kilovoltages and by monoenergetic electrons in an electron microscope. Some considerations are given on the sensitivity of the nuclear-track plate used in these experiments.

I. INTRODUCTION

SINCE the introduction of the Kodak Nuclear-Track Emulsion, Type NT2a,[1] which permits the recording of electron tracks, studies have been made of such tracks produced in various ways. Apart from the interest which these photographs have simply as records of electrons, they provide data for estimating the relation between the length of the track and the electron energy, and also the sensitivity of the plates to electrons. Accurate determination of these properties would require a source of monoenergetic electrons (the energy of which can be varied). Since such an apparatus was not available, measurements have been made from electron records produced by exposure to x-rays generated at different voltages. A few measurements were also made with mono-

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* Communication No. 1204-H from the Kodak Research Laboratories.
[1] R. W. Berriman, Nature 161, 432 (1948).