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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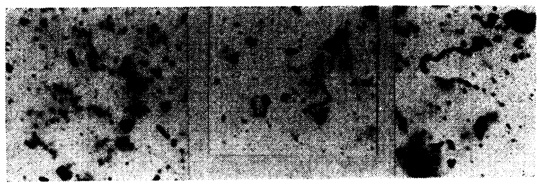
Four different methods of obtaining electron tracks in nuclear-track plates are described. Electron tracks have been produced by x-rays, by natural radioactive decay, by exposures in an electron microscope, and by feeble, induced radioactivity. A first attempt at establishing the range-energy relationship 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.

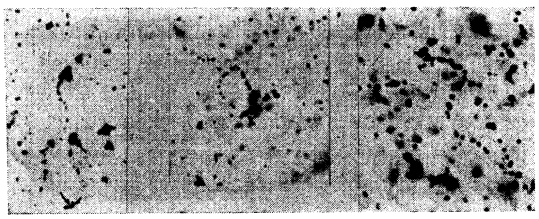
I. INTRODUCTION

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-

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



35 kv (no filter) 65 kv (0.2-mm Cu filter) 130 kv (1.8-mm Cu filter)



200 kv (10-mm Cu filter) 200 kv (10-mm Cu filter) 200 kv (10-mm Cu filter) Mosaic

FIGS. 1–6. (Reading from top left to bottom right.) Tracks of electrons released by x-rays at various kilovoltages. Magnification, 2200×.

energetic electrons produced in the electron microscope. Accurate measurements are being carried out by means of an electron spectrograph by M. A. S. Ross and B. Zajac of the University of Edinburgh.

II. RECORDING OF ELECTRON TRACKS BY VARIOUS METHODS

A. Electron Tracks Produced by X-Rays of Increasing Hardness

If NT2a Plates are exposed to x-rays, electrons are released from the silver bromide grains and leave tracks in the emulsion which are visible under the microscope. Heavily filtered heterogeneous x-rays have been used, and for each quality of x-rays electron tracks of different lengths have been obtained, as described in Section III. As the kilovoltage is increased, the quantum energy of the x-radiation is increased and electrons of higher energy are produced, leaving tracks of increasing lengths in the emulsion. Typical electron tracks obtained with various kilovoltages of x-rays are shown in the photomicrographs (Figs. 1–6). The exposure conditions for the tracks of electrons released at 35, 65, 130, and 200 kilovolts are given in Table I.

The plates were all processed for 20 minutes at

TABLE I.

kv	Filtration (in mm Cu)	mA	Exposure time (in seconds)
35	Inherent filtration of x-ray tube	0.5	2
50	0.05	0.5	2
65	0.2	1.5	2
69*	Selective filter of $CaWO_4$		
100	1.3	4.0	2
130	1.8	5.0	2
200	10.0	4.0	7

* Monochromatic K_α-radiation of platinum.

65°F in Kodinol Developer,** using the following formula:

	Metric	British
Kodinol Developer (concentrated)	100 cc	8 fluid oz.
Potassium bromide (10 percent solution)	30 cc	2.4 fluid oz.
Water to make	1000 cc	80 fluid oz.

Figures 1–6 give further direct evidence for the assumption that the effect of x-rays on the photographic emulsion is due, at least to some

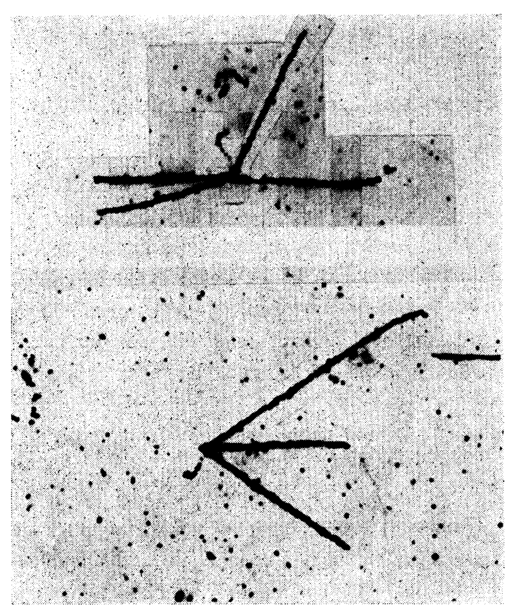


FIG. 7. Photomicrographic mosaics of plane projections of three-dimensional radiothorium stars, at the origin of which electron tracks are seen. Second electron track visible in (a) may be the end of a track of an electron of higher energy arising from the same origin. Magnification, 2400×.

** Kodinol Developer is not available in the United States. Similar results may be obtained using Kodak D-19 Developer and development for 20 minutes at 68°F.

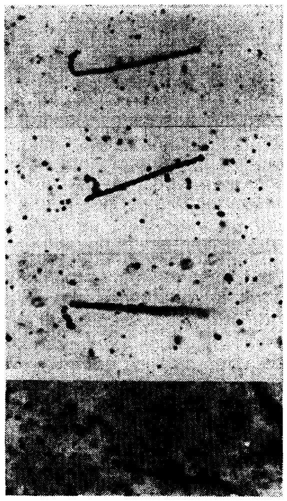


FIG. 8. Photomicrographs of alpha-particle tracks from uranium I; beta-tracks probably due to decay of uranium X_1. Beta-ray energy (d) should (according to Table II) correspond roughly to 35 kv. Magnification, 2000×.

extent, to the release of electrons that travel beyond the grain that initially absorbs the x-ray quantum, and produce developability in neighboring grains.

B. Electron Tracks in Radioactive Decay

It was expected that one of the applications of the NT2a Plates might be the recording of tracks of beta-particles emitted in radioactive decay of the natural radioactive elements. The plates were bathed in different concentrations of aqueous radioactive solutions of thorium and uranium nitrate. Since a small amount of a radioactive paint containing radium was available, tests were also made by soaking the plates in a diluted solution of this material. The concentrations used were 5, 3, 1, 0.1, and 0.01 percent by weight. Three plates were bathed for ten minutes in each of these solutions and then dried in light-tight cardboard boxes. One series was kept for 1 day, one for 1 week, and one for 4 weeks before processing. Examination of these plates under the microscope revealed no electron tracks from solutions with substantially greater concentrations than 0.1 percent, which appeared to be the optimum, although the number of alpha-particle tracks per unit area was considerable and roughly proportional to the concentrations. With 5 percent and 3 percent solutions, a desensitization effect was observed, since the grain density of alpha-particle tracks became strikingly smaller than in the plates of smaller concentrations. The number of electron tracks found was greater for longer exposure times; it was very considerably smaller than that of alpha-particle tracks, and hundreds of tracks and star formations had to be scanned in order to find electron tracks arising from the origin of the stars or single alpha-particle tracks. A few of these were photomicrographed (Figs. 7–9).

The scarcity of electron tracks in the emulsion is not surprising, when it is considered that only low energy electrons up to approximately 80 kv (Section III) can be recorded at present, and that tracks of high energy electrons will show only if the ends of their tracks happen to pass through the emulsion.

A greater number of electron tracks arising from radioactive decay were, however, obtained when blotting paper was impregnated with 10 percent radioactive solutions and placed about 1 mm distant from the emulsion. Some of the electrons lose their energy in the blotting paper and the ends of their tracks are then recorded in the emulsion.

C. Exposures in the Electron Microscope

Some preliminary exposures were made to 50-kv and 25-kv monoenergetic electrons in a Metropolitan-Vickers electron microscope. A

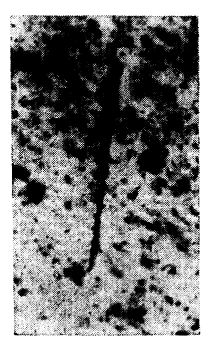


FIG. 9. Alpha-track due to thorium C and beta-track may be due to parent element, thorium B, which has been ejected before the alpha-emission. A second track of a beta-particle is believed to arise from the same origin. This may be attributed to the beta-emission of thorium C″. Identity of thorium C alpha-track was found by measuring the length of the track. Magnification, 2000×.

photomicrograph of such an exposure at 50 kv is shown in Fig. 10, and sections through heavily exposed emulsions (at 25 and 50 kv) are shown in Fig. 11. It is worth noting that the formation of electron tracks in photographic emulsions sets a limit to the resolving power in electron micrography in the same way that diffusion of light does in ordinary photomicrography.

D. Recording of Electron Tracks by Induced Radioactivity

Although electron tracks occurring in radioactive decay have been shown (Section IIB), tests have been carried out in order to check whether electrons from very feeble, induced radioactivity can be detected by photographic emulsions. An NT2a Plate covered by an aluminum foil 50 microns thick was exposed for five days to fast neutrons arising from a beryllium target, which was bombarded by alpha-particles from a 5-millicurie polonium source. According to the three possible nuclear reactions (n,p), (n,α), (n,γ) stated below, electrons are emitted by the decay of the three radioactive isotopes formed in this way:

$${}_{13}\mathrm{Al}^{27}+{}_{0}n^{1}\rightarrow{}_{12}\mathrm{Mg}^{27}+\mathrm{H}^{1}$$
$${}_{12}\mathrm{Mg}^{27}\rightarrow{}_{13}\mathrm{Al}^{27}+\beta^{-}{}_{(1.8\ \mathrm{Mev})}T=10.2\ \mathrm{min.}; \quad (1)$$
$${}_{13}\mathrm{Al}^{27}+{}_{0}n^{1}\rightarrow{}_{11}\mathrm{Na}^{24}+{}_{2}\mathrm{He}^{4}$$
$${}_{11}\mathrm{Na}^{24}\rightarrow{}_{12}\mathrm{Mg}^{24}+\beta^{-}{}_{(1.4\ \mathrm{Mev})}T=14.8\ \mathrm{hr.}; \quad (2)$$
$${}_{13}\mathrm{Al}^{27}+{}_{0}n^{1}\rightarrow{}_{13}\mathrm{Al}^{28}+h\nu$$
$${}_{13}\mathrm{Al}^{28}\rightarrow{}_{14}\mathrm{Si}^{28}+\beta^{-}{}_{(3.3\ \mathrm{Mev})}T=2.4\ \mathrm{min.} \quad (3)$$

A greater yield of these reactions can be obtained only by thermal neutrons. A slowing down of neutrons by a moderator was not attempted, because of the reduction of the neutron flux per unit area with increasing distance from the source. Thus, only a feeble, induced radioactivity can be expected. A photomicrograph of a few electron tracks obtained in this way is shown in Fig. 12.

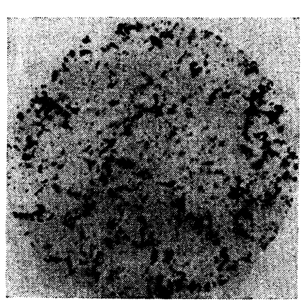


FIG. 10. Electron micrograph: 50-kv electrons. Magnification, 1200×

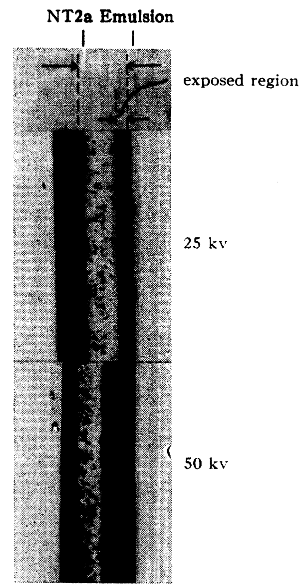


FIG. 11. Sections through NT2a Emulsion exposed to 25- and 50-kv monoenergetic electrons in electron microscope. Heavy density on the left of the sections is caused by another exposed emulsion on which the sections of NT2a Emulsion were placed. Magnification, 900×.

E. Auger Tracks

While scanning the electron tracks produced by x-rays, we observed that some tracks showed clumping of grains at the beginning and at the end of the tracks. (See arrows in Fig. 4.) This phenomenon can probably be attributed to the Auger effect.[2] Auger observed in Wilson cloud-chamber photographs a similar effect while using a heavy gas, such as argon, in the chamber. When he diluted this heavy gas by 95 percent of hydrogen, it could be seen that some of the tracks branched off at the beginning to form secondary tracks, which were due to the formation of secondary electrons. This led him to conclude that the K_α photon generated when an L electron jumps into a K-orbit frequently acts photoelectrically on another L or M electron in the same atom, which is thus ejected. Since silver and bromine are relatively heavy atoms,

[2] P. Auger, J. de phys. et rad. 6, 205 (1925).

it may be concluded that the cause of heavy ionization at the beginning of some tracks may be similar to that interpreted by Auger.

III. RELATIONSHIP BETWEEN ENERGY AND RANGE OF ELECTRON TRACKS

The release of photoelectrons by absorption of x-rays in the photographic emulsion is based on the photoelectric effect and can be represented by $h\nu=(m v^2/2)+w_K$, where $h\nu$ is the energy of the incident x-ray quantum, $m v^2/2$ is the kinetic energy of the electron released, and w_K is the energy required to remove an electron from the K level of the atom. The kinetic energy of the electron will then be $h\nu-w_K$. Similar effects will occur at each of the other absorbing levels, since the primary radiation, $h\nu$, may be absorbed in any of the energy levels in the atom. Hence, for an incident radiation of frequency, ν, groups of electrons will be released having energies, $h\nu-w_{K1}$, $h\nu-w_{L1}$, $h\nu-w_{L2}$, etc. With the increase of incident quantum energies, electron groups of higher energies will be released. If heterogeneous x-rays are used, a continuous electron spectrum comprising a wide range of electron energies can be expected. The greatest electron energy which will be produced by a heterogeneous x-ray beam will then be equal to the energy of the shortest x-ray wave-length present in the beam minus the work function equivalent to the highest electron level.

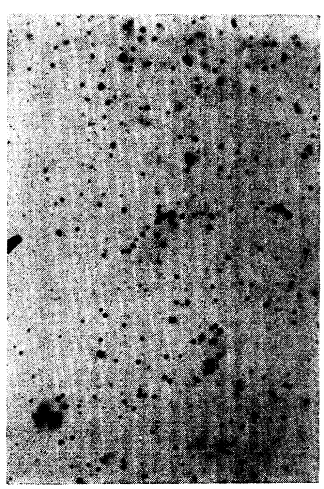


FIG. 12. Electron tracks produced by induced radioactivity. Magnification, 2500×.

In addition to the photoelectric absorption effect, the modified Compton effect will occur. This results in the emission of recoil electrons, the energies of which depend upon the angle of the scattered photon with respect to the direction of the primary beam. The energies of recoil electrons are considerably smaller than those of the photoelectrons for the same quantum energy incident and are independent of the material through which the photons pass.

Experimental

A series of strips of NT2a Plates, with an emulsion layer 30μ thick, were exposed to heavily filtered x-rays generated at increasing kilovoltages. The exposure times were so adjusted that the number of electron tracks revealed in the microscope field was roughly constant for all qualities of radiations. The kilovoltages, the corresponding filtrations, the milliamperage, and the exposure times are listed in Table I. The focus-plate distance for all exposures was 100 centimeters. At 69 kv the monochromatic K_α radiation of platinum was used. This radiation, corresponding to a wave-length of $\lambda=0.178$A, was obtained as a secondary characteristic radiation excited by the absorption of primary x-rays. The characteristic radiation was selectively filtered by a Kodak Ultra-Speed (calcium tungstate back) Intensifying Screen and was checked by means of an x-ray spectrograph.

The plates were given standard development, as mentioned in Section II, and then scanned by means of a projection microscope using an oil-immersion objective and an eyepiece. The number of developed grains of each track visible in the projected field was counted and plotted against the frequency of tracks. The counting was done independently by two observers, who, in order to avoid any bias during counting, were not told the generating kilovoltage at which the plates were exposed. For each kilovoltage, 50 tracks were counted and the grain number-frequency curve obtained is shown in Fig. 13. It can be seen from this graph that the maximum frequency shifts slightly towards a greater number of grains with increasing kilovoltage up to 65 kv and from 130–200 kv. No marked increase was found for the maximum number of grains with increasing kilovoltage, as might be expected.

The exposure with monochromatic radiation was made, as it was thought that this radiation might increase the maximum frequency towards a greater number of grains if compared with the 65-kv heterogeneous radiation. This is, however, not indicated by the distribution for monochromatic rays equivalent to 69 kv (Fig. 14). In this case, 200 tracks were counted.

Since the method of counting tracks in the field was very tedious, it was thought that a more satisfactory way of relating the range of tracks and the energy would result from scanning many hundreds of tracks of which only the longest tracks are selected and counted. This was done, and in a few cases where the tracks were at almost glancing angle with respects to the plane of the plate, length measurements of the curved path of tracks were made. The results of these measurements are tabulated in Table II.

TABLE II.

kv	Maximum number of grains	Range in microns (curved path)	Schönland and Varder (Calc. in microns)	Column 3 ×1.4 (curved path in microns)
35	13	8	6.1	8.5
50	18	14	10.6	14.8
65	16	—	16.7	23.4
69*	18	—	18.6	26.0
80	—	—	23.1	32.0
100	18	—	—	—
130	28	35	—	—
200	27	—	—	—

* Monochromatic K_α-radiation of platinum.

It will be seen from Table II that the maximum numbers of grains counted do not vary appreciably between 50–100 kv. No satisfactory explanation for this result can be given at present. It is possible, however, that the maximum number of grains obtainable is at 50 kv and that the greater counts obtained at 130- and 200-kv x-rays are due to erroneous counting. This uncertainty in counting may well be visualized by reference to Figs. 3, 5, and 6, which show photomicrographs of long electron tracks taken at 130- and 200-kv x-rays. It is difficult to decide whether these represent single or multiple tracks. Another possible explanation for the constancy of the number of grains counted between 50–100 kv might be the rising proportion of Compton recoil electrons which have, on the average, a considerably shorter range than the photoelectrons. However, the probability of the formation of recoil electrons, which is very high compared with that of the formation of photoelectrons from light atoms, such as are present in gelatin, decreases if heavy absorbing atoms, such as silver and bromine, are present. The effect mentioned is, therefore, difficult to understand if we consider the high silver bromide/gelatin ratio of the NT2a Plate. No marked influence can be expected from the ratio of the volumes of silver bromide to gelatin, which is approximately unity, since the ratio of the number of photo- and recoil electrons released depends basically upon the weight concerned. Some consideration

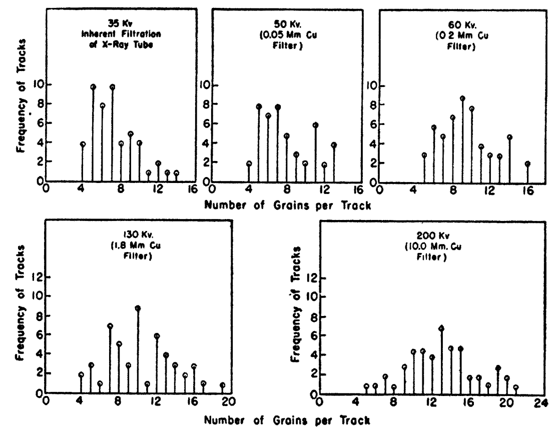


FIG. 13. Grain number-frequency curve.

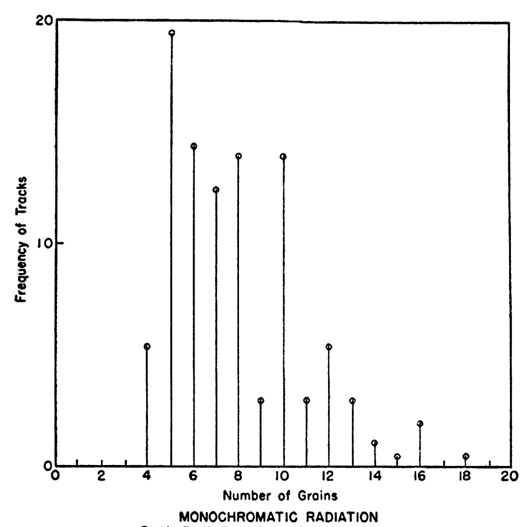


FIG. 14. Monochromatic radiation. Platinum K_α radiation ($\lambda = 0.178$A~69 kilovolts).

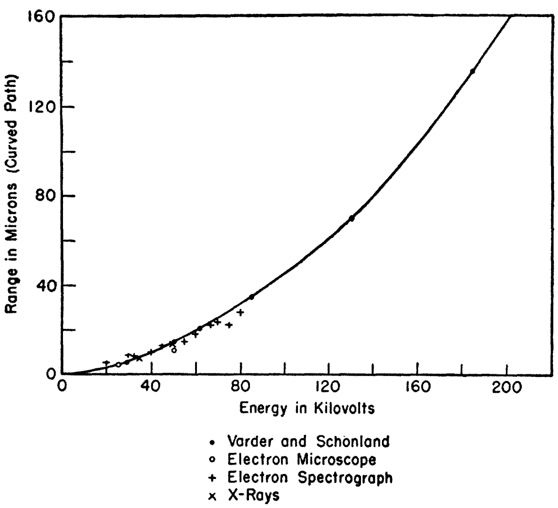


FIG. 15. Relationship between range in emulsion and energy (in E kv).

might be given to the release of electrons from the glass support, but no plausible explanation could be derived from such an effect either.

Length measurements were also carried out on sections of emulsions that had been subjected to heavy exposures to monoenergetic electrons in the electron microscope (Fig. 11). The plates were exposed with the electron beam perpendicular to the plane of the plate, and the widths of the exposed region of sections of the emulsions were measured. These widths can be regarded as the straight-line range of the electron path, since the majority of the tracks form zigzag lines. According to Williams,[3] the curved paths of electrons in metal should be, on the average, some 40 percent greater than the thickness of the metal foil. In Table III, the widths of the exposed region and of the curved path of tracks are given in microns. The values are the means of 15 measurements at 25 kv and at 50 kv in the electron microscope. The value at 50 kv is below that obtained with x-rays, which may be a result of the shrinkage effect of the emulsion in the plane perpendicular to the plate.

TABLE III.

kv	Width of exposed region (in microns)	Curved path of tracks (in microns)
25	3.2	4.5
50	8.2	11.5

[3] E. J. Williams, Proc. Roy. Soc. (London) **130A**, 310 (1931).

After these length measurements were made, it appeared of interest to see how the results obtained agree with measurements taken by other workers. The thickness of various metals necessary to stop electrons of different velocities was determined by Schönland[4] and by Varder.[5] These workers found that the thickness is dependent only upon the mass per unit area. The range values of Schönland and Varder were converted into lengths in microns for the mass per unit area of NT2a Emulsion, and these values are quoted in column 3 of Table II. Column 4 shows the values of column 3 multiplied by 1.4 (curved path).

From the values in column 3 (Table II) and from the considerations regarding the constancy of grain numbers between 65 and 100 kv, it may be concluded that the maximum energy of electrons which can be recorded with the NT2a Emulsion will be at about 80 kv. This figure and the data just given might serve as a guide until more accurate measurements have been made by means of an electron spectrograph. Ross and Zajac[6] have carried out some preliminary measurements with the electron spectrograph, and their data are roughly in agreement with those tabulated.

Figure 15 shows the relationship between range

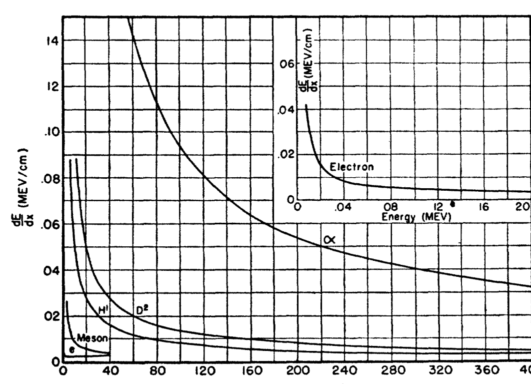


FIG. 16. Relationship between energy loss per centimeter of air and energy for alpha-particles, deuterons, protons, mesons, and electrons.

[4] B. F. J. Schönland, Proc. Roy. Soc. (London) **104A**, 235 (1923); **108A**, 187 (1925).
[5] R. W. Varder, Phil. Mag. **29**, 726 (1915).
[6] M. A. S. Ross and B. Zajac, private communication.

in emulsion and energy (in E kv). The values obtained by x-rays, by the electron microscope, and by the electron spectrograph are indicated in the graph. The values taken with the electron spectrograph are preliminary data kindly sent by M. A. S. Ross and B. Zajac,[7] of the University of Edinburgh. The curve is plotted up to 200 kv from the values of Varder and Schönland converted into lengths in microns for the mass per unit area of the NT2a Emulsion and multiplied by 1.4.

IV. CONSIDERATIONS ON THE SENSITIVITY OF NT2a PLATES

In a recent paper, Webb[8] has shown the relationship between the energy loss per centimeter of air, (dE/dx) (Mev/cm), and energy for alpha-particles, deuterons, protons, mesons, and electrons (Fig. 16). Assuming that a safe limit for the recording of electron tracks with the NT2a Plate is 50 kv, this would correspond to an energy loss of 0.007 Mev per centimeter of air. The limiting energy values up to which the recording of other particles can be expected with this plate would be

200 Mev for deuterons,
100 Mev for protons,
>400 Mev for alpha-particles, and
10 Mev for mesons.

The number of ion pairs produced in a silver bromide grain for a given loss of a particle per centimeter in air can be computed, according to Webb, by

$$\text{Ion pairs/AgBr grain} = n \times s \times (\text{Ev.}_{\text{air}}/\text{Ev.}_{\text{AgBr}}) \times d,$$

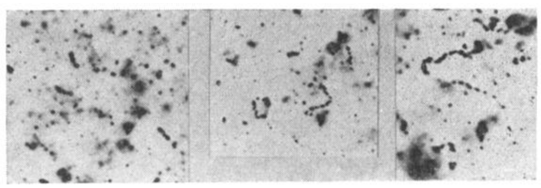
where n = number of ion pairs per micron of air, s = stopping power of emulsion for electrons (at 50 kv = 3.7 cm air/1.4 10^{-3} cm AgBr = 2600), Ev._{air} = number of electron volts required per ion pair in air = 35 v, Ev._{AgBr} = number of electon volts required per ion pair in AgBr = 7.6 v, and d = diameter of grain in NT2a = 0.3 micron.

Since one ion pair in air corresponds to an energy dissipation of approximately 35 v, the energy loss of 0.007 Mev per centimeter of air (electrons at 50 kv) is equivalent to 0.7/35 = 0.02 ion pair per micron in air. Using the figures above, the number of ion pairs required to render a grain of NT2a Plate developable would be 72. Since the number of ionizations decreases only slowly with increasing energy of electrons, and reaches a minimum at about 500–1000 kv (according to Heitler[9]), it can be assumed that an increase of sensitivity above that of NT2a Emulsion of about three times would be required for the recording of tracks of any electron energy. Similar conclusions were drawn by Berriman.[10]

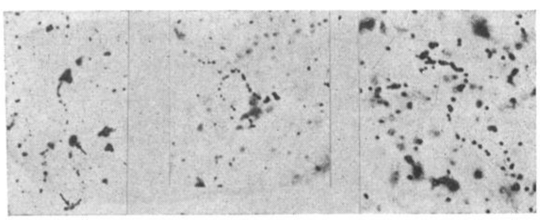
ACKNOWLEDGMENT

The author wishes to thank Messrs. E. B. Kennedy and G. P. Cooke, who were responsible for much of the experimental work described in this paper.

[7] M. A. S. Ross and B. Zajac, Nature **162**, 923 (1948).
[8] J. H. Webb, Phys. Rev. **74**, 511 (1948).
[9] W. Heitler, *The Quantum Theory of Radiation* (Oxford University Press, London, 1944), p. 222.
[10] R. W. Berriman, Paper given at a Symposium on Photography in Nuclear Research, on March 18, 1948, at the Royal Photographic Society, London.



35 kv (no filter) | 65 kv (0.2-mm Cu filter) | 130 kv (1.8-mm Cu filter)



200 kv (10-mm Cu filter) | 200 kv (10-mm Cu filter) | 200 kv (10-mm Cu filter) Mosaic

FIGS. 1–6. (Reading from top left to bottom right.) Tracks of electrons released by x-rays at various kilovoltages. Magnification, 2200×.

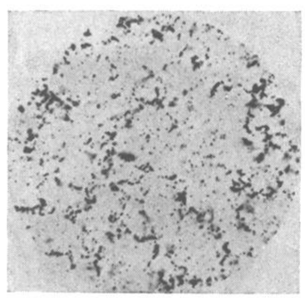


FIG. 10. Electron micrograph: 50-kv electrons.
Magnification, 1200×

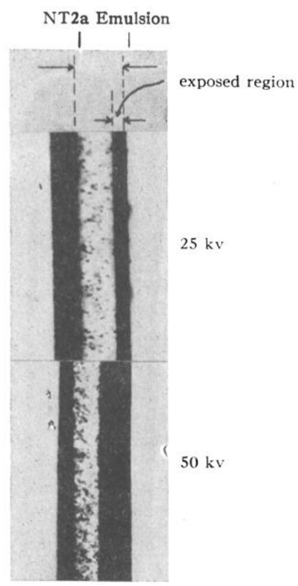


FIG. 11. Sections through NT2a Emulsion exposed to 25- and 50-kv monoenergetic electrons in electron microscope. Heavy density on the left of the sections is caused by another exposed emulsion on which the sections of NT2a Emulsion were placed. Magnification, 900×.

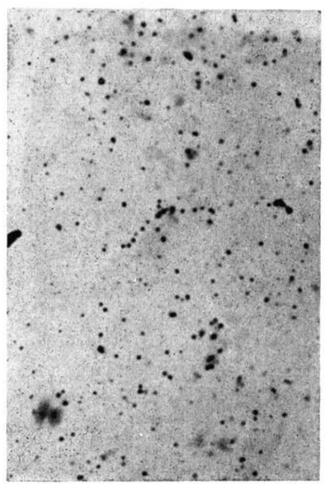
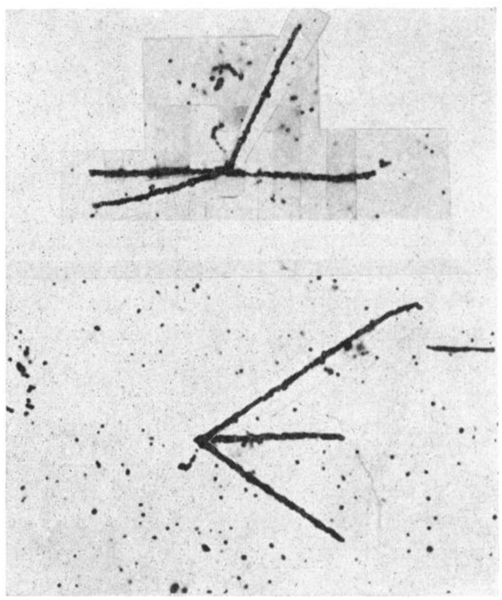


FIG. 12. Electron tracks produced by induced radioactivity.
Magnification, 2500×.



(a)

(b)

FIG. 7. Photomicrographic mosaics of plane projections of three-dimensional radiothorium stars, at the origin of which electron tracks are seen. Second electron track visible in (a) may be the end of a track of an electron of higher energy arising from the same origin. Magnification, 2400×.

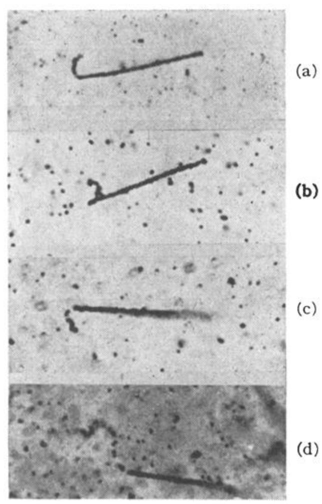


FIG. 8. Photomicrographs of alpha-particle tracks from uranium I; beta-tracks probably due to decay of uranium X_1. Beta-ray energy (d) should (according to Table II) correspond roughly to 35 kv. Magnification, 2000×.

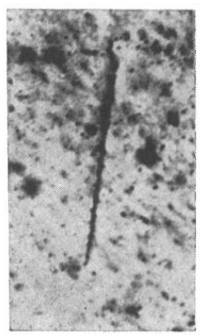


FIG. 9. Alpha-track due to thorium C and beta-track may be due to parent element, thorium B, which has been ejected before the alpha-emission. A second track of a beta-particle is believed to arise from the same origin. This may be attributed to the beta-emission of thorium C″. Identity of thorium C alpha-track was found by measuring the length of the track. Magnification, 2000×.