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On the Photographic Action of α, β and γ Rays emitted from Radioactive Substances.

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With 3 Plates.

1. *Introduction.* In 1909 one of the writers[1] showed that whenever an *α* particle strikes a grain of silver halide in the sensitive film of photographic plates, that grain becomes subsequently capable of development. It was also shown that this is the case throughout the whole range of *α* rays, no matter what may be the quality of the plate. It is remarkable that the behaviour of the photographic plate regarding this phenomenon should obey such a simple law, when we take into consideration its complex behaviour with regard to light.

From the atomistic point of view, on the other hand, the above result is also highly interesting, as it affords a third independent method of recording the emission of a single *α* particle, in addition to the electrical method devised by Rutherford and Geiger[2], and the scintillation method first systematically studied by Regener[3].

In the light of the above investigation, it was to be anticipated that if *α* particles were projected tangentially on a photographic plate, the halide grains encountered by each *α* particle would on development appear in a train. This effect

1) S. Kinoshita, Proc. Roy. Soc. A, **83** (1910), p. 432.
2) E. Rutherford and H. Geiger, Proc. Roy. Soc. A, **81** (1908), p. 141.
3) E. Regener, Verh. d. D. Phys. Ges. **10** (1908), pp. 78 and 351.

was examined first by Reinganum[1]. On a photograph obtained in this way, silver grains were found arranged on distinct lines, showing themselves as the α ray tracks. He also found that some of the tracks showed the effect of scattering. Experiments on this subject were later made in detail by Michl[2] and by Mayer[3]. Some microphotographs of the α ray tracks showing deflexions were obtained by Walmsley and Makower[4].

For the last three years, we have been engaged in devising some simple methods of obtaining radial α ray tracks and making some investigations upon them. The present paper contains the main results in this line of investigation, most of which appeared separately in other publications[5].

2. *Methods of obtaining radial α ray tracks.* In investigating the photographic traces of α rays it was thought most advantageous to work with the smallest possible source of the rays. For, if a point source be established and placed on a photographic plate, the expelled α particles will leave on it a set of radial traces, which can be followed with greater ease and certainty[6].

The source which we first utilized was a fine needle point coated with a trace of active deposit of radium[7]. This was prepared by lightly rubbing the point on a small ball of iron which had previously been exposed to a few millicuries of radium emanation. By bringing the needle in contact with a photographic plate, a part of the active deposit was detached from the needle and left on the plate at the point of contact. Leaving the plate for a certain time to allow a sufficient number of α particles

1) M. Reinganum, Phys. Zeits. **12** (1911), p. 1076; Verh. d. D. Phys. Ges. **13** (1911), p. 848.

2) W. Michl, Akad. Wiss. Wien. Ber. **121**, 2a, (1912), p. 1431.

3) F. Mayer, Ann. d. Phys. **41** (1913), p. 931.

4) H. P. Walmsley and W. Makower, Proc. Phys. Soc. **26** (1914), p. 261.

5) S. Kinoshita and H. Ikeuti, Proc. Tokyo Math.-Phys. Soc. **7** (1914), p. 360; also Phil. Mag. **29** (1915), p. 420; H. Ikeuti, Phil. Mag. **32** (1916), p. 129; Proc. Tokyo Math.-Phys. Soc. **8** (1916), p. 465.

6) In the first publication, we have referred to the paper of Michl of which we learnt through the Beiblätter z. d. Ann. d. Phys. and the Science Abstracts, as the number of the Wien. Ber. containing the original paper could at that time not be found in our Library. In these reviews nothing was mentioned of the method by which α ray tracks had been obtained. When we obtained the original paper afterwards, we found that the method employed by him had, in some ways, been similar to that of ours. However, his lines of investigation were different from ours.

7) For the case of polonium and of active deposits of thorium, R. R. Sahni's paper in Phil. Mag. **29** (1915), p. 831 may be referred to.

to emit, it was developed when a fine spot became visible to the naked eye. On examining the plate under a microscope, the said spot was found to consist of a multitude of separate trails of silver grains running radially from a common centre.

In the photographs taken in this way, however, there is around the centre a dark area, which is no doubt the portion where the active needle touched the plate during the above said process. In this case, the radial tracks do not emerge at the centre but at the rim of the dark area. Since the tip of the needle had the shape of a truncated cone terminating in a flat section of about 10 μ in diameter, it was impossible to obtain by this method a photograph showing no central dark area. Still, this method was found useful when, as reference will be made later, deflexions of α ray tracks had to be investigated.

Several trials were made to obtain photographs with nuclei as small as possible. When an iron ball coated with the active deposit was held above a photographic plate and knocked with a hammer or the like, some fine dust particles adhering to the iron ball seemed to be set free by the shock and to settle down on the plate, becoming thus the sources of the α radiations. On developing the plate several spots appeared and some of them were found to possess nuclei whose linear dimensions are very small compared with the length of the α ray track. The spots themselves were so small that they were hardly detected by the naked eye.

To obtain a large number of these spots, it was found effective to strike the photographic plate directly with the active iron ball on the film side. To illustrate the general feature of the photographs obtained in this way, one of the plates is reproduced in fig. 1, enlarged 120 diameters. The *irregular* dark areas seen in this figure are the spots where the plate was struck by the iron ball. Around these areas, there can be seen several circular spots, each of which consists of a set of α ray tracks running radially from a common centre.

It may be remarked that, in a photograph in which a large number of α ray tracks radiate from a common centre, each trail does not appear distinct from the others along the whole length, but, in the vicinity of the centre, comes very close to or overlaps the neighbouring ones, even when the radiant nucleus is practically a point. This effect also gives rise to a dark area at the centre, which has no definite shape. The dimensions of the dark area vary of course with the number of the trails.

3. *Two different types of radial α ray tracks.* As microscopic examinations at once show, the trails of grains may, in general, be divided into two different types.

In the first type, the trails emerge directly at the centre or, in case when the dark nucleus is present, at the rim of it. Consequently, when a set of homogeneous α rays have been utilized, all the tracks terminate very nearly at the circumference of a circle drawn around the centre, and present themselves as a halo (figs. 2–8), resembling the pleochroic halo seen in minerals such as biotite, and investigated in detail by Joly[1].

Without question, the radial tracks do not all lie on planes parallel to the surface of the emulsion film, and as can be traced by focussing the microscope, some of them are running oblique to the surface. Since the film on ordinary photographic plates has a thickness equivalent to only about two centimetres of air in stopping α rays, the photographic halo obtained on these plates can never be that of a complete sphere.

The trails belonging to the second type spread out around the centre over a wide region of no definite boundary, as can be seen in fig. 9, which is reproduced in the same magnification as the haloes in figs. 2–8. In this case, most trails are found to have their seat within the uppermost layer of the film, showing that they are the tracks of the α particles projected tangentially to the surface of the film from the part of the source just above the surface. At first sight, some of the trails seem to be much longer than those constituting the haloes. Closer inspection, however, shows that this is only apparent and that each of them consists of two or more elementary trails following one another in succession.

1) J. Joly, Phil. Mag. **13** (1907), p. 381; **19** (1910), p. 327; J. Joly and A. L. Fletcher, Phil. Mag. **19** (1910), p. 630.

4. *Haloes due to radium C.* These can be obtained by utilizing as the source of α rays the active deposit of radium, in which radium A has already disappeared. Figs. 2–4 are the microphotographs of these haloes, enlarged 500 diameters. It will be of interest to see the different stages of formation. In the halo in fig. 2 about 45 tracks are to be seen, this being of course the number of the tracks on a plane focussed in reproducing the microphotograph and forming therefore only a small fraction of the total. The haloes in figs. 3 and 4 are seen to contain about 70 and 120 tracks respectively.

The ends of the tracks constituting a halo do not lie strictly on a circle owing to the difference in the struggling of the rays through the medium. We have therefore taken as the radius of the halo the radius of the circle drawn so as to pass through the ends of most of the far reaching tracks. The radii of the haloes determined in this way vary slightly, but their smallest limit is found to be 52 μ. Since, on the other hand, isolated tracks of this length are found in such photographs as fig. 9, this may be taken as the range of the α rays from radium C in the substance, so that the radiant nuclei of these haloes must be very small.

5. *Haloes due to radium A and radium C.* To obtain haloes of this kind, we have exposed an iron ball to radium emanation for a few minutes and performed the above stated process as quickly as possible. These haloes are reproduced in figs. 5–8, in the same magnification as before. They indicate that the tracks of a set of homogeneous α rays from radium A give rise to another concentric circle inside that due to radium C, as in the case of the pleochroic halo.

It will be seen that in fig. 5 the outer circle is more conspicuous than the inner one, while with fig. 6 the reverse is the case. Which of the circles comes out more conspicuously depends upon in what proportion radium A and radium C have been mixed in the source utilized.

The inner circle is in each case smaller than the outer by 16 μ in radius. Thus the ratio of the ranges in the substance of the two α rays becomes (52–16) : 52 or ·69, which is the same as its value in air. According to Marsden and Richardson[1], the above ratio for silver is much higher, amounting to ·86. In the present case, the absorption of the α rays is mainly due to gelatine, which is the main composition of the sensitive film, and this substance seems to be of a character similar to air concerning absorption.

6. *Number of silver grains along an α ray track.* Silver grains along an α ray track are naturally not equidistant. To find the distribution, Ikeuti has measured, by means of the ocular micrometer of a microscope, the distance d between successive grains on the track for a large number of pairs of the grains. When the number of pairs of grains was plotted against the corresponding values of d, and a mean curve was drawn, this showed a maximum at $d=1{\cdot}85\ \mu$ in the case of Ilford Process Plates, falling quickly to zero on the side of the origin and somewhat slowly on the other side. From these measurements the mean value of d was calculated to be $2{\cdot}85\ \mu$. This corresponds to 350 grains per millimetre of the track. Since the longest tracks of the α rays from radium A and radium C are 36 and 52 μ respectively, they will consist on the average of 12·6 and 18·2 grains respectively. It must, however, be remembered that the actual numbers are subjected to fairly large fluctuations.

7. *The nature of the photographic action of α particles.* Alpha ray tracks obtained in a sensitive film do not exhibit even the slightest difference along their whole range; neither in the compactness of the grains nor in their size. This is a very important fact and confirms conclusively the previous experiment of Kinoshita[2], in which the constancy of the photographic action of an α particle along the whole range was photometrically established. Now, if it be considered that there are all possibilities of regarding ionisations in a solid and in a gas to be of a similar type, the question may arise, why the photographic action, which is nothing but the result of ionisation, should not be represented by the characteristic curve known as Bragg's ionisation curve. As a matter of fact, darkening in the pleochroic halo is particularly pronounced near the boundary, in spite of that the number of α

1) E. Marsden and H. Richardson, Phil. Mag. **25** (1918), p. 191.

2) *l. c.*

particles traversed, taken per unit volume, is least in that region, and this fact can be explained as the result of an intense ionisation near the extreme end of the range of the α particles[1].

A theory put forward by Kinoshita to explain the singularity of the photographic action was that, if some of the halide molecules within a grain are initially ionised by one or more α particles, the whole grain becomes subsequently capable of development, but the reduction cannot extend to other grains which have not been initially ionised. When the film is completely developed, all the grains struck by the α particles are reduced to a constant limit, which depends on the size of halide grains in the emulsion film but not on the degree of the primary ionisation in them, and we thus obtain silver grains as a secondary consequence of the ionisation, so that the photographic action is constant throughout the whole range of the α particles in the substance. A further consideration will be presented later[2].

In variance with the above theory, Michl[3] states that only a part of the halide grains encountered by an α particle become subsequently developable. This conclusion is based on a microscopic comparison between the compactness of silver grains on a photographic plate which was obtained by exposing it to light, and the diffuse arrangement of the grains on an α ray track obtained on the same plate.

In order to show that the above reasoning is by no means adequate, the original paper of Kinoshita must be again referred to. It was shown that the photographic density D of a photographic plate produced by normally falling α particles varies with their number n per unit area of the plate as

$$D=D_0(1-e^{-cn}), \qquad (1)$$

where D_0 is the maximum value of D attainable by an indefinitely large number of the α particles, and c is a constant depending on the quality and the thickness of the emulsion film on the plate.

As is generally known, the photometric density of a plate is

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1) J. Joly, *l. c.*; E. Rutherford, 'Radioactive Substances and their Radiations' (1913), p. 310.

2) *c. f.* p. 15.

3) *l. c.*

proportional to the mass of silver contained in a unit area of the plate. Therefore, if it be assumed, as a first approximation, that all the grains are of equal mass, the above equation may be written in terms of the number s of the grains per unit area in the plate.

$$s=s_0\,(1-e^{-cn}), \tag{2}$$

where s_0 is the value of s for the plate for which $D=D_0$ and would be the total number of the halide grains initially present in the emulsion film per unit area.

Consequently, the number of the falling α particles required to increase one more developable grain will be

$$\frac{dn}{ds}=\frac{1}{c\,(s_0-s)}. \tag{3}$$

If we take the corresponding values of s and n in a plate of very small density, s is negligibly small compared with s_0. In this case, the above equation reduces to

$$\frac{dn}{ds}=\frac{1}{cs_0}.$$

Giving values experimentally found:
$c=1{\cdot}18.10^{-8}$ and $s_0=1{\cdot}16.10^{8}$ for a Wratten Instantaneous Plate, and $c={\cdot}93.10^{-8}$ and $s_0={\cdot}97.10^{8}$ for a Wratten Ordinary Plate,

$$\frac{dn}{ds}= {\cdot}73 \text{ for the Instantaneous Plate, and}$$
$$= 1{\cdot}1 \text{ for the Ordinary Plate.}$$

On examining microscopically, it was found that the Instantaneous Plate of very high density was entirely covered with silver grains, while the Ordinary Plate of maximum density was almost covered with grains, but about one-tenth of the area was estimated as allowing α particles to pass through without contact with the grains, and that in an Instantaneous Plate of small density about one-third of the grains were overlapping others, while in an Ordinary Plate the overlapping was practically negligible, so that one α particle did not strike more than one halide grain.

Taking these facts into consideration, it can be concluded with certainty that the number of α particles required to change one halide grain into the developable state is *one*, whenever it strikes the grain. For, if, in the case of the Instantaneous Plate, the number of the overlapping be taken as 37 per cent. of the total, each α particle would in the average change 1·37 grains on its passage through the film; in other words, the number of α particles required to change one halide grain would be $\frac{1}{1\cdot37}$ or ·73, which is the value of $\frac{dn}{ds}$ calculated from the values of c and s_0 for that plate. Similarly, in the case of the Ordinary Plate, if the area uncovered with the grains be taken as 10 per cent. of the totals, 1·1 α particles on average would be required to change one halide grain. We are thus lead to the conclusion that one α particle is sufficient to change a halide grain into the developable state, whenever it encounters the grain and whatever may be the quality of the plate.

In dealing with an α ray track, it must be remembered that we are observing those grains only, the centres of which lie, as will be directly shown, within a very narrow cylinder of a cross section equal to that of the halide grains, but not those having their centres outside the cylinder. Since grains at various depths, the difference of which is much greater than their linear dimensions, can be seen simultaneously in a microscopic vision even of fairly high magnification, mere comparison of the compactness of visible grains on the two different plates, one acted on by light and the other by individual α particles, would never lead to the conclusion already stated.

8. *The size of grains.* The size of the silver grains has been determined, as far as we know, only by microscopic methods, visual, projecting or photographing. These methods, however, do not seem to give very reliable results, unless care is taken with regard to the diffraction phenomenon, because the grains to be measured are so small that their linear dimensions are of the same order of magnitude as the wave-lengths of the visible light. In the following, we shall describe two methods of deducing the size of halide grains from the data obtained in the investigation on the α ray photographs. Although the methods are rather indirect, they may still be of use in practical application.

(a). Having proved that each halide grain is rendered capable of development whenever it is encountered by an α particle, equation (3) which can be written in the form:

$$ds = c\,(s_0 - s)\,dn, \qquad (3')$$

may be interpreted as: the rate at which the number of acted or developable halide grains increases with the falling α particles is proportional to the number of halide grains not yet acted upon. And the proportional factor c will be the probability of one halide grain being struck by an α particle, and consequently, the ratio of the area of the projection of each grain to a plane perpendicular to the direction of motion of the α particles to a unit area.

Therefore, if r_0 is the average radius of the halide grains, supposing these to be spherical,

$$c = \frac{\pi r_0}{1},$$

from which

$$r_0 = \left(\frac{c}{\pi}\right)^{\frac{1}{2}}. \qquad (4)$$

Thus, from the values of c already given, we obtain:

$r_0 = {\cdot}61\ \mu$ for the Instantaneous Plate, and
$r_0 = {\cdot}54\ \mu$ for the Ordinary Plate.

If each grain of silver bromide of radius r_0 be completely reduced to metallic silver, its mass m and radius r would be

$$m = \frac{4}{3}\pi r_0^3 \rho_0 \times \frac{108}{188} = \frac{4}{3}\pi\left(\frac{c}{\pi}\right)^{\frac{3}{2}} \rho_0 \times \frac{108}{188}, \qquad (5)$$

$$r = \left(\frac{108}{188}\,\frac{\rho_0}{\rho}\right)^{\frac{1}{3}} r_0 = \left(\frac{108}{188}\,\frac{\rho_0}{\rho}\right)^{\frac{1}{3}} \left(\frac{c}{\pi}\right)^{\frac{1}{2}}, \qquad (6)$$

where ρ_0 and ρ are the densities of silver bromide and metallic silver respectively.

As a verification of the result, the mass M of silver contained in a unit area of a plate deduced from the mass m calculated by equation (5) and the number s of the silver grains per unit area, *viz.*

$$M = ms = \frac{4}{3}\pi\left(\frac{c}{\pi}\right)^{\frac{3}{2}} \rho_0\, s \times \frac{108}{188} \qquad (7)$$

may be compared with that deduced from its photometric density D, *viz.*

$$M = kD, \tag{8}$$

where k is the photometric constant, being for green light equal to $1{\cdot}03.10^{-4}$ gr. per sq. cm. of the plate.

Giving the following values experimentally found:

$s = 1{\cdot}29.10^7$ for an Instantaneous Plate, for which $D = {\cdot}412$, and
$s = 1{\cdot}06.10^7$ for an Ordinary Plate, for which $D = {\cdot}210$, we get
$M = 4{\cdot}52.10^{-5}$ gr. per sq. cm. by (7) and
$M = 4{\cdot}24.10^{-5}$ gr. per sq. cm. by (8) for the Instantaneous Plate,
and
$M = 2{\cdot}55.10^{-5}$ gr. per sq. cm. by (7) and
$M = 2{\cdot}16.10^{-5}$ gr. per sq. cm. by (8) for the Ordinary Plate.

Bearing in mind the fact that the conversion of silver bromide to metallic silver is not carried out to completion, the agreement between the values obtained by the two methods is seen to be quite satisfactory.

The average radius of silver grains calculated by equation (6) corresponds, for the reason just stated, to the superior limit. It is

$r = {\cdot}43\ \mu$ for the Instantaneous Plate, and
$r = {\cdot}38\ \mu$ for the Ordinary Plate.

The size of the silver grains was actually measured under a microscope, by means of an ocular micrometer for a number of grains. It was found that the above calculated values of r are within the range over which the size of the observed grains varies.

(b). Ikeuti showed that the average radius r_0 of halide grains can also be deduced from the average number s_1 of silver grains per unit length along an α ray track, when the thickness of the emulsion film and the mass of silver halide contained per unit area of it are known from other determinations.

Remembering that every halide grain becomes subsequently developable whenever struck by an α particle, it can easily be seen that silver grains presenting themselves as an α ray track on a developed plate must have their centres within a circular cylinder drawn round the path of the a particle with radius equal to that of halide grains. Consequently, s_1, which is the reciprocal of the average distance d between successive grains along the track, will be the number of the halide grains having their centres within the cylinder of unit length; thus $\frac{s_1}{\pi r_0^2}$ will be the total number of the halide grains initially present in the emulsion film per unit volume.

If t is the thickness of the film, the total numbar s_0 of the halide grains in a unit area of the plate will be

$$s_0=\frac{s_1 t}{\pi r_0^2}.$$

Another relation between s_0 and r_0 can be obtained from a consideration on the amount M_0 of silver bromide contained in a unit area of the plate,

$$M_0=\frac{4}{3}\pi\, r_0^3\, \rho_0\, s_0,$$

where ρ_0 is, as before, the density of silver bromide.

From the above two equations, we obtain

$$r_0=\frac{3}{4}\,\frac{M_0}{\rho_0 s_1 t}.$$

From a set of measurements made on an Ilford Process Plate, *e.g.*

$s_1=3,500$ per cm.,

$M_0=9{\cdot}6.10^{-4}$ gr. per sq. cm., which was determined by chemical analysis, and

$t=15\ \mu$, which was measured by Zeiss's Dickenmesser,

the average radius of the halide grain is found to be

$$r_0={\cdot}22\ \mu.$$

By using the relation in equation (6), the average radius of the silver grains becomes

$$r=\left(\frac{108}{188}\frac{\rho_0}{\rho}\right)^{\frac{1}{3}} r_0={\cdot}15\ \mu.$$

A suitable photometer being at present not at our disposal, we are unable to compare this result with that deduced from the photometric density. It may only be noted that the above calculated value of r is also within the range over which the size of the grains actually measured by means of the microscope varies.

9. *Deflexions of α particles on the passage through the emulsion film.* Evidences have already been given by the previously cited investigators that some of the α particles suffer sudden deflexions on the passage through the emulsion film.

In dealing with the deflexions of α rays, the importance of utilizing a single source may be emphasized. If a set of radial α ray tracks are obtained with an active needle in the way already described, the possibility is excluded that two tracks, running in different directions, happen to fall at a common point and present themselves as if they were a single track suffering a sudden deflexion.

In the microphotograph in fig. 10, which is enlarged 1,500 diameters, the tracks of four α particles, running from left to right, are visible. The source of the particles lies outside the figure to the left about 15 centimetres on this scale from the left end. We can see that while the second α particle from the top passed straight on, the other three suffered sudden deflexions of 10° to 15° downwards after traversing some distances nearly parallel to one another.

We have examined hundreds of sets of the radial α ray tracks, but so far we have not been able to find any which can be said with certainty to have suffered the deflexion of an angle so large as 90°. The smallness of the proportion of the largely deflected tracks to the total will not be inconsistent with the experimental results arrived at by Geiger[1] and by Geiger and Marsden[2], and also with the theory worked out by Rutherford[3]. It must be borne in mind that we are, in the present case, observing only such deflexions, which have taken place within a very thin layer bounded by planes parallel to the surface of the film, whereas the deflexions occur, in general, equally in all planes which contain the initial line of motion.

1) H. Geiger, Proc. Roy. Soc. A, **81** (1908), p. 174, and **83** (1910), p. 492.
2) H. Geiger and E. Marsden, Proc. Roy. Soc. A, **82** (1909), p. 495.
3) E. Rutherford, Phil. Mag. **21** (1911), p. 669.

When a photographic plate was placed in contact with a flat piece of glass coated with the active deposit of radium and thus exposed to the α rays coming out of the source of large area, a considerable proportion of their tracks seemed to have suffered large deflexions. This is not in conformity with the result just stated. It appears likely that most, if not all, of the tracks which look as if they were deflected are only apparently so. This view is supported by the fact that there were as many tracks showing large deflexions as small ones.

Experiments made with the object of finding if the magnetic field has any influence upon the α ray tracks gave negative results. In a field of ten thousand gauss, up to which the experiment was extended, an α particle with a velocity of 10^9 cm. per sec. (one-half of the initial velocity of the α particles from radium C) will describe a path for which the radius of curvature is as great as 20 centimetres. It would not be possible to recognize such a slight curvature, as the track under examination is only 52 μ at most in length.

10. *The photographic action of β particles.* It has long been known that β rays possess the property of acting on a photographic plate; but owing to difficulties involved in the experiments, very little is known about the effect of an individual β particle.

When the α and β rays from the active deposit of radium were allowed to fall separately upon two areas on a thinly coated plate, the photometric density produced by the β rays was, for an equal number of the particles, found to be one-sixth to one-eighth of that produced by the α rays. Therefore in going a unit distance through the emulsion film, a β particle brings out at most the above fraction only of the silver grains which an α particle would, the actual path of the β particle being, on account of deflexions, greater than the thickness of the film. It is thus to be anticipated that the silver grains acted on by a β particle follow one another with too wide intervals to present themselves as the track of the particle, much more so when the liability of the particle in suffering deflexions through matter is considered. The difference shown by the tracks in air of α and β particles in the photograph obtained by

C. T. R. Wilson in his well-known condensation experiment may, though not quite similar, serve as an analogy. While an α ray track would still be detectable, if the number of water drops per unit length were reduced to one-thousandth, say, in a β ray track this would be far from being the case. It must be remembered that β particles will suffer greater deflexions in gelatine films than in air. A direct evidence for the above conclusion is found in the fact that it is possible to obtain a halo due to the α particles from radium C, outside of which no perceptible track of any sort is present, although the source emits simultaneously β particles as well and the most of them travel far beyond the boundary of the halo.

The photographic action of β particles should be explained by an hypothesis of the kind we have made in the case of α particles; for, in the latter the basis of the hypothesis is the ionisation of halide molecules, which is the effect also common to β particles. We shall consider that a halide grain becomes capable of development when it is encountered by a β particle, but only when the encounter takes place under certain favourable conditions. This seems plausible, because a β particle, while it would encounter on a path per unit length as many halide grains as an α particle does, renders developable silver grains of only a small part compared with those similarly affected by an α particle. Since it is very likely that, whenever a halide grain is encountered by a β particle, some halide molecules in it, however few in number, are ionised, we may assume that the process of development in the grain cannot start unless the number of initially ionised halide molecules exceeds a certain value. An analogous phenomenon is met with in the case of an electric discharge between two electrodes. The discharge is facilitated and starts at a lower but definite potential when the interposed gas is initially ionised beyond a certain degree. The above assumption apparently contradicts what has been said in the case of α particles; but it seems quite possible to an α particle, which in gases shows an ionising action several thousand times stronger than that of a β particle, to ionise a number of halide molecules over the threshold value, whenever it strikes a halide grain.

11. *Considerations on the photographic action of γ rays.* The general feature of the photographic action of γ rays may be inferred from the facts hitherto accumulated. As is well known, X rays do not directly ionise the molecules of a gas which the rays traverse, but liberate from them corpuscular radiation which is responsible for the ionisation[1]. The velocity of the emitted corpuscles is independent of the nature of the emitter and depends only upon the wave-length of the exciting X rays, the smaller the wave-length the greater the velocity. The excitation of the corpuscular radiation by X rays is not limited to gases but is also true of solids and liquids.

There is every reason to believe that this is the case with γ rays, which, as we know, differ from X rays only in wave-length. It has already been shown that the corpuscular radiation set up by γ rays from a radium salt is nearly as swift as the primary β rays emitted by it[2]. Thus, the effect of exposing a photographic plate to X or γ rays will be that corpuscular radiation is set up throughout the exposed portion of the plate. Since individual β particles leave no detectable tracks of silver grains on a photographic plate, it will be impossible to obtain a track of X or γ rays on a photographic plate similar to that of X rays illustrated by the photographs obtained by C. T. R. Wilson in the condensation method. It will be evident that the halide grains rendered capable of development by a flash of X or γ rays are scattered very diffusely throughout the volume of the emulsion film, but with no definite arrangement.

In an experiment we have exposed a plate to a flash of X rays through an extremely narrow slit between two thick brass plates, to see if any particular effects were produced in- and outside the region upon which the X rays fell. Microscopic examination of the plate gave negative results, as was naturally to be expected.

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1) C. G. Barkla and L. Simons, Phil. Mag. **23** (1912), p. 317; C. T. R. Wilson, Proc. Roy. Soc. A, **87** (1912), p. 277; C. G. Barkla and A. J. Philpot, Phil. Mag. **25** (1913), p. 832.

2) A. S. Eve, Phil. Mag. **8** (1904), p. 669; S. J. Allen, Phys. Rev. **23** (1906), p. 65.

In conclusion, we wish to thank Professor Nagaoka for placing the resources of the Laboratory at our disposal and for his continual interest during the progress of this investigation.

Physical Laboratory, University of Tokyo.

Explanation of the Plates.

Fig. 1. The general feature of a plate containing several spots, each of which consists of a number of radial α ray tracks. The isolated spot at the top and the large one at the bottom of the figure are reproduced in figs. 5 and 6 respectively in a higher magnification.

Figs. 2–4. Haloes due to radium C, at different stages of formation.

Figs. 5–8. Haloes due to radium A and C. In each halo two concentric circles are to be seen. The inner circle is due to radium A and the outer to radium C. In fig. 5 the inner circle is more conspicuous than the outer one, while in fig. 6 the reverse is the case.

Fig. 9. The tracks of α particles emitted from a nucleus of radium C, reaching to various distances.

Fig. 10. α ray tracks showing sudden bents. On this figure are visible the tracks of four α particles which passed from left to right. Three of them suffered sudden deflxions.

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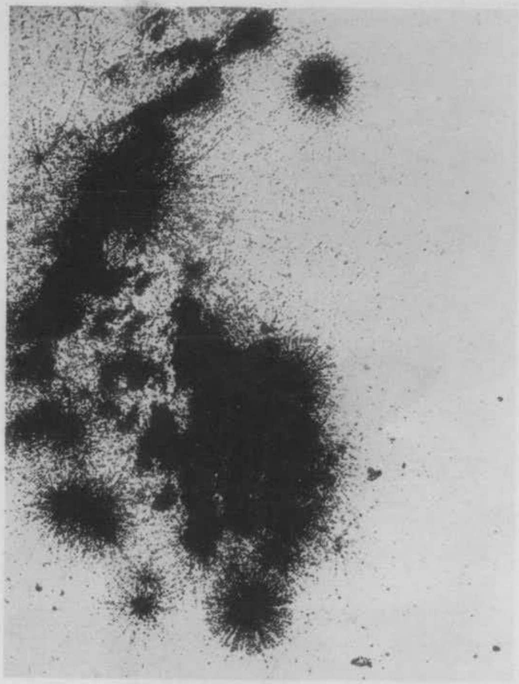

Fig. 1. ×120.

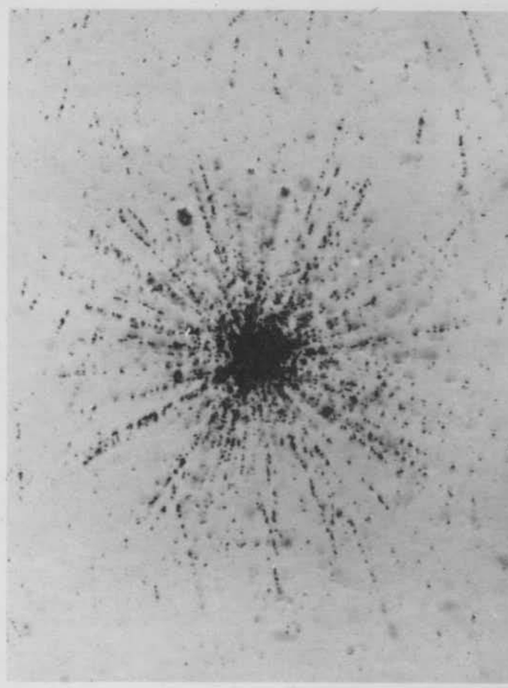

Fig. 2. ×500.

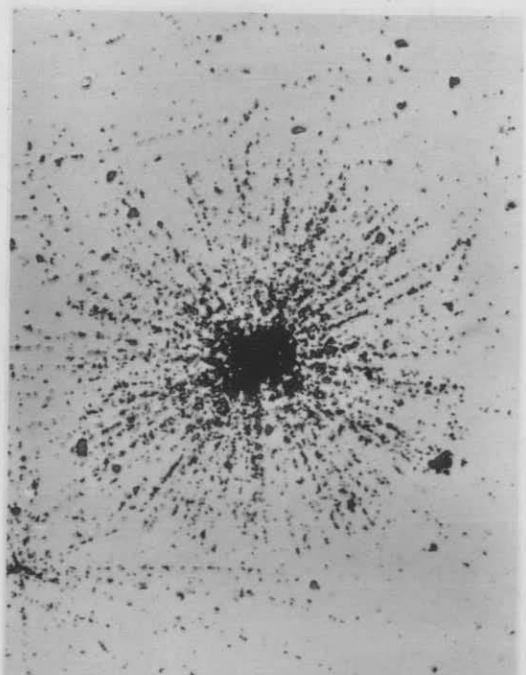

Fig. 3. ×500.

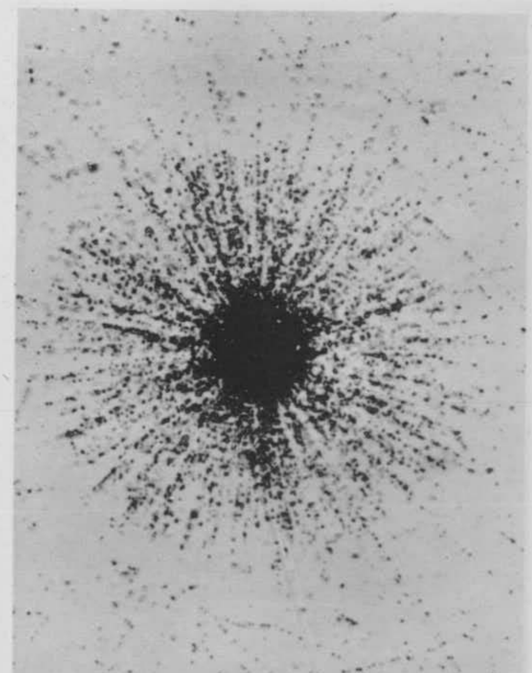

Fig. 4. ×500.

S. Kinoshita and H. Ikeuti: The Photographic Action of the α, β and γ Rays emitted from Radioactive Substances.

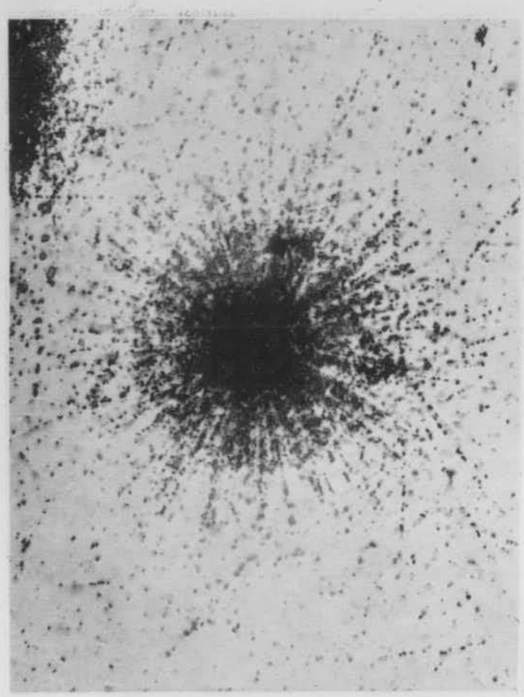

Fig. 5. ×500.

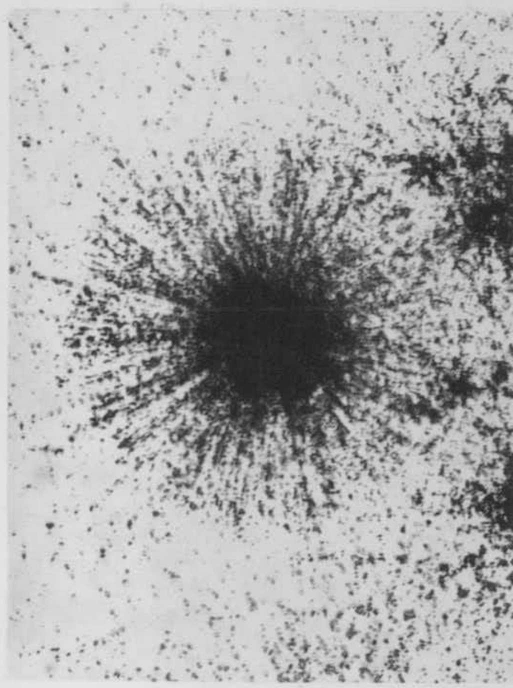

Fig. 6. ×500.

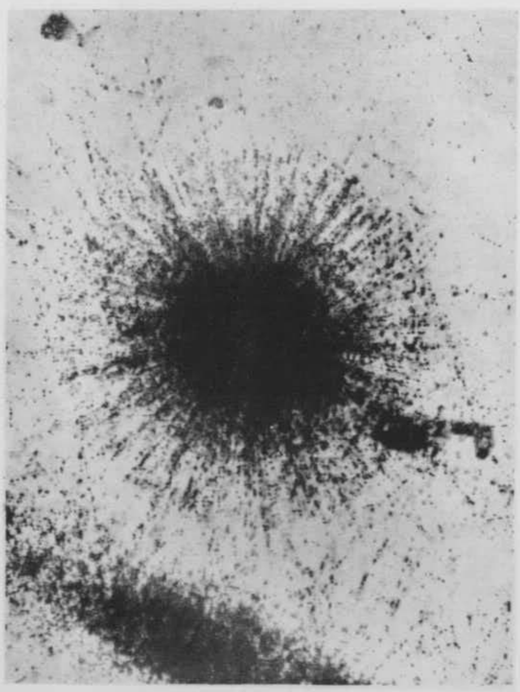

Fig. 7. ×500.

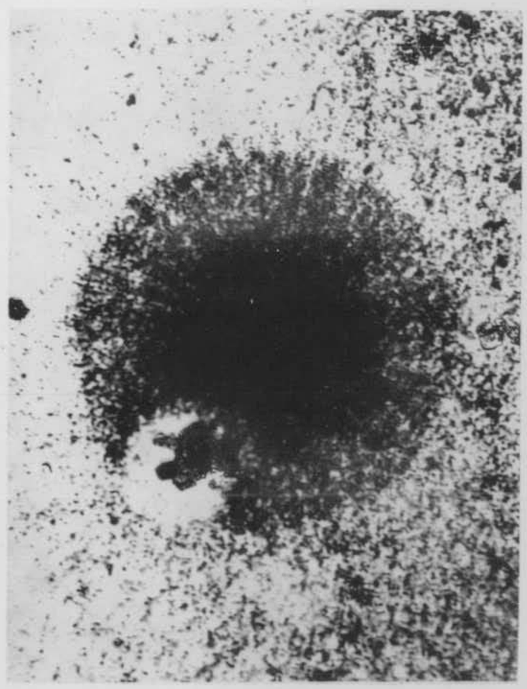

Fig. 8. ×500.

S. Kinoshita and H. Ikeuti: The Photographic Action of the α, β and γ Rays emitted from Radioactive Substances.

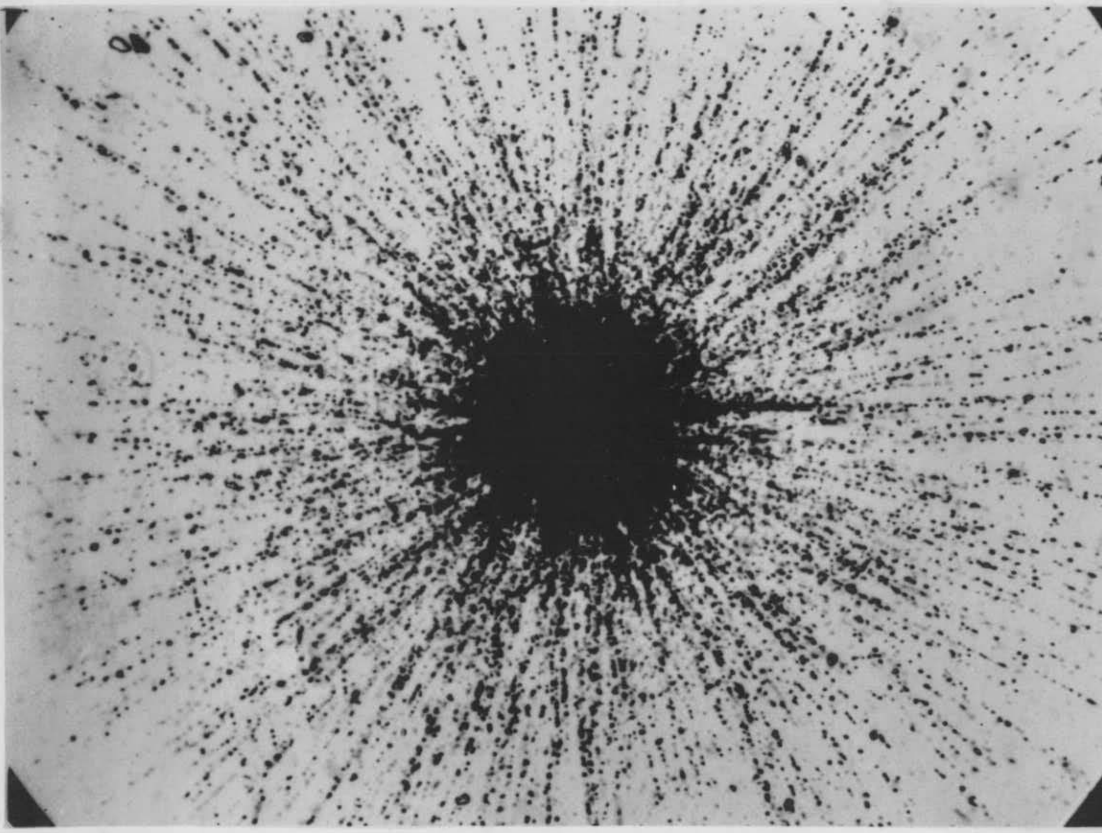

Fig. 9. ×500.

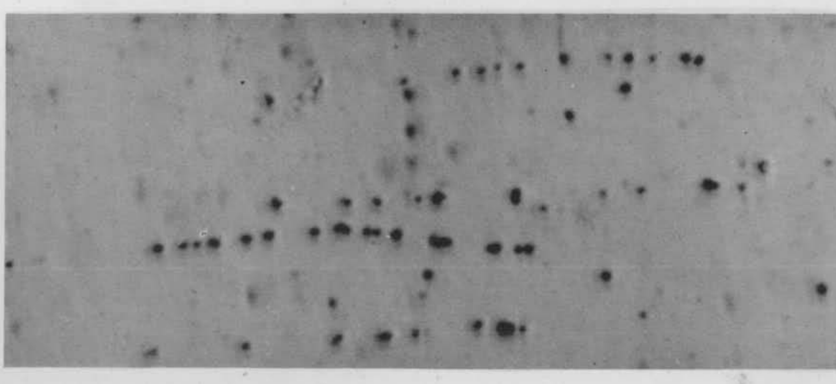

Fig. 10. ×1,500.

ERRATA.

p. 1, *For* **Hadime IKEUTI** *read* **Hazime IKEUT.**

p. 5, eighth line from bottom. *For* outer *read* inner.

„ seventh line from bottom. *For* inner *read* outer.

p. 10, fourteenth line from top, *For* $c=\frac{\pi r_\circ}{1}$ *read* $c=\frac{\pi r_\circ^2}{1}$

p. 12, eighth line from top, *For* numbar *read* number.