THE TRACKS OF THE α-PARTICLES OF THORIUM AND ITS PRODUCTS.

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It has been known for many years[1] that α-particles can be recorded by allowing them to pass through a photographic emulsion. The emulsion consists of numerous grains of silver bromide, embedded in gelatine, and an α-particle traversing the emulsion will pass through those grains which lie on its path. These grains are affected by the α-particle, in much the same way as they are affected by light in the ordinary photographic process. When the plate is developed, these grains are accordingly reduced by the chemical action of the developer, and become grains of solid silver. Unaffected grains are dissolved out by a solution of hypo. In the developed plate, therefore, the paths of α-particles which have passed through the emulsion are visible as rows of black grains. A high magnification is necessary for observing these tracks.

More recently the technique has been improved, and the method has been applied in several investigations.[2,3,4,5,6] Special plates are used, coated with the new Ilford " R " emulsion. This emulsion is specially suitable for recording α-particle tracks, and was originally prepared in the Ilford laboratories for this purpose.[7] The grains are very small, the mean diameter being only $0 \cdot 3\,\mu$. The stopping power of the emulsion for α-particles is about 1400 times greater than that of air; one cm. path in air is equivalent to $7\,\mu$ in the emulsion, and the mean number of grains in a path of this length is five. The number of grains corresponding to a given length of path is naturally subject to considerable variations.

In order to record the tracks of the α-particles emitted by thorium and its products, the following method was used. A weak solution of thorium nitrate was prepared, and a plate was placed in the solution for about twenty minutes. The plate was then removed and dried, all the operations, of course, being carried out in complete darkness in order to avoid fogging.

When the plate dries, the solute remains in the gelatine, so that thorium atoms are distributed uniformly through the emulsion. These atoms remain in practically fixed positions during the progress of the experiment. After an interval of three days, the plate was developed and fixed in the normal manner, and after drying was examined microscopically. (For this purpose we use a fluorite dry objective corrected for use with uncovered objects, N.A. = 0·90, and a total magnification of 900 ×. It is impracticable to use an oil-immersion objective.)

Many more tracks are observed than can be ascribed to thorium alone, since all the members of the thorium series are present. In the complete transformation from thorium to thorium D, an atom emits six α-particles. The series is well known, and the relevant data are given in the following table:

Element	Type of Disintegration	Range of α-particle in cms. air at 18°C.	Decay constant	Half-value period
Thorium	α	2·93	$1{\cdot}33\times10^{-18}$ sec.$^{-1}$	$1{\cdot}65\times10^{10}$ years
Mesothorium I	β		$3{\cdot}28\times10^{-9}$	6·7 years
Mesothorium II	β		$3{\cdot}14\times10^{-5}$	6·1 hours
Radiothorium	α	4·05	$1{\cdot}16\times10^{-8}$	1·9 years
Thorium X	α	4·40	$2{\cdot}20\times10^{-6}$	3·6 days
Thorium Emanation	α	5·11	$1{\cdot}27\times10^{-2}$	54·5 secs.
Thorium A	α	5·74	4·78	0·14 secs.
Thorium B	β		$1{\cdot}82\times10^{-5}$	10·6 hours
Thorium C	α & β	4·82	$1{\cdot}91\times10^{-4}$	60·5 mins.
Thorium C′	α	8·70	ca. 10^{11}	very short
Thorium C″	β		$3{\cdot}61\times10^{-3}$	3·2 mins.
Thorium D	stable			

The series branches at Th. C, which disintegrates *either* with the emission of an α-particle, to give Th. C″, *or* with the emission of a β-particle, to give Th. C′. Thus the α-particles of Th. C and Th. C′ are alternative; in the course of its disintegration an atom emits either one or the other, but not both.

Let us suppose that a particular atom of thorium in the emulsion emits its α-particle. The chance that the same atom will emit a further α-particle during the period of the experiment is very small. Indeed it will be several years before any appreciable fraction of the atoms have reached the stage of emitting the next α-particle, since the half-value periods of MsTh. I and RdTh. are large. The tracks should therefore occur singly, and several tracks radiating from a single point are not to be expected. Many such single tracks due to the α-particles of thorium are actually observed.

Radiothorium is an isotope of thorium, and is probably present in the original solution in the equilibrium amount. This element is thus introduced into the emulsion with the thorium, and the amount of RdTh. present will not vary appreciably during the period of the experiment. We can therefore calculate the amounts of the subsequent products which are present at any later time. Let the decay constants of a series of consecutive elements be denoted by $\lambda_1, \lambda_2, \lambda_3 \ldots\ldots$ and suppose that the first element is the only one which is present initially. Then the amount of the nth element at the time t is given by the expression

$$N(t) = c_1 e^{-\lambda_1 t} + c_2 e^{-\lambda_2 t} + \ldots\ldots\ldots\ldots\ldots + c_n e^{-\lambda_n t}$$

where

$$c_1 = N_0 . \lambda_1 \lambda_2 \ldots\ldots \lambda_{n-1} \,/\, (\lambda_2 - \lambda_1)(\lambda_3 - \lambda_1)\ldots\ldots(\lambda_n - \lambda_1)$$

$$c_2 = N_0 . \lambda_1 \lambda_2 \ldots\ldots \lambda_{n-1} \,/\, (\lambda_1 - \lambda_2)(\lambda_3 - \lambda_2)\ldots\ldots(\lambda_n - \lambda_2)$$

$\ldots\ldots\ldots\ldots\ldots\ldots$ etc.

N_0 = number of atoms present initially.

We are chiefly interested in the amounts of the elements Th. X, Th. B, and Th. D which are present in the emulsion, since the short-lived elements will be present only in infinitesimal amounts. Before an atom of Th. X can be formed, its parent RdTh. atom must have emitted an α-particle, so that every Th. X atom present should be the point of origin of a single track in the emulsion. Before an atom of Th. B can be formed, four α-particles must be emitted, and therefore every Th. B atom present should be at the point of origin of four tracks. Similarly, five tracks should radiate from every Th. D atom present.

If the calculation be made, for example, with $t = 3 \cdot 10^5$ seconds ($= 3\frac{1}{2}$ days, the approximate exposure in the experiments), we find the relative numbers of atoms are as follows:

Th. X	(origin of a single track)	25
Th. B	(centre of a "star" of four tracks)	2·6
Th. D	(centre of a "star" of five tracks)	31

In the original solution, some of the later products of disintegration (Th. X and Th. B) are already present, though not necessàrily in equilibrium amount. These will give some additional tracks. The transition Th. X→Th. B will produce a "star" of three tracks; the transition Th. X → Th. D will produce a "star" of four tracks; and the transition Th. B → Th. D will give a single track, either long (8·7 cms.) or short (4·8 cms.)

It is clear, then, that a plate should show, on examination:

(*a*) Single tracks corresponding to the α-particles of Th.

(*b*) A number of "stars" consisting of five tracks radiating from a point.

(*c*) A somewhat smaller number of single tracks corresponding to the α-particles of RdTh.

(*d*) A few "stars" of three or four tracks.

(*e*) A few single tracks corresponding to the α-particles of Th. C and Th. C′.

The observations confirm these conclusions. It is not possible, however, to check the relative numbers of single tracks and "stars", except very roughly. The reason for this is that the atoms are situated at all depths in the emulsion, and the α-particles are emitted in all directions. Only tracks lying in or near the horizontal plane are suitable for measurement, and as many of the α-particles pass out of the emulsion altogether, their tracks are incomplete. This will be easily understood when it is remembered that the thickness of the emulsion does not exceed 14 μ, the equivalent of 2 cms. of air.

The identification of individual tracks presents great difficulty. It has been pointed out previously that the tracks corresponding to α-particles of a given energy show considerable variations in length, and a critical discussion of these variations has been given.[6] If a large number of tracks, produced by α-particles of the same energy, are measured, a frequency curve of the measurements can be constructed. From this curve it is possible to obtain a quantity known as the "extrapolated length" of the tracks, which can be determined with some accuracy, and which is strictly proportional to the range in air of the same particles. From the measurement of a *single* track, however, there is a large uncertainty in the determination of the corresponding range in air. In a "star" of five tracks, usually only the long track corresponding to the Th.C′ α-particle (8·7 cms.) can be identified with certainty. The ranges of the other α-particles do not differ sufficiently for the tracks to be distinguished unambiguously.

Many hundreds of "stars" have been observed. In order to obtain a photomicrograph of a "star", all five tracks must be approximately in the horizontal plane, and the central point must not be too near the surface of the emulsion, or some tracks may fail to be recorded. The probability that an individual track will lie sufficiently near the horizontal plane for this purpose is certainly not more than $\frac{1}{8}$, and the probability that all the five tracks will be complete and well-placed for photomicrography is probably not more than 1/50,000. One can therefore hardly expect to find a perfect specimen. After some weeks of careful searching two "stars" have been found, however, in which the conditions are nearly fulfilled. These are shown in the diagram (Figs. 1 and 2), which may be compared with the photomicrographs (Figs. 3 and 4). Measurements of the tracks give the following results :

Track	Length in μ	Calculated range in cms. of air	Remarks
Figs. 1 & 3—			
a	57	8·51	α-particle of Th. C′
b	28·5	4·26	
c	26·3	3·93	
d	..	..	track incomplete
e	28·5	4·26	
Figs. 2 & 4—			
a	56	8·36	α-particle of Th. C′
b	34	5·08	? Th. Em. or Th. A
c	29	4·33	
d	6·3	..	track incomplete
e	..	..	track out of focus

The chief interest of the present observations lies in the fact that we have the whole history of an isolated radioactive atom, recorded as a "star" in the emulsion. Other methods of studying radioactive transformations, on the other hand, give only the "average history" of a large number of atoms, or else, as in the Wilson chamber, give a record of the transformations occurring during a very small interval of time.

There is some evidence that an atom may occasionally diffuse through the emulsion for a perceptible distance during the progress of the experiment. Occasionally instances are found in which the five tracks belonging, apparently, to the same "star", do not diverge from exactly the same origin. This suggests that the atom has moved, say, in the time between the emission of the first α-particle and the emission of the last four. The extent of this apparent movement is not more than three or four μ. This is a point, however, upon which it is difficult to come to any certain conclusion, for the

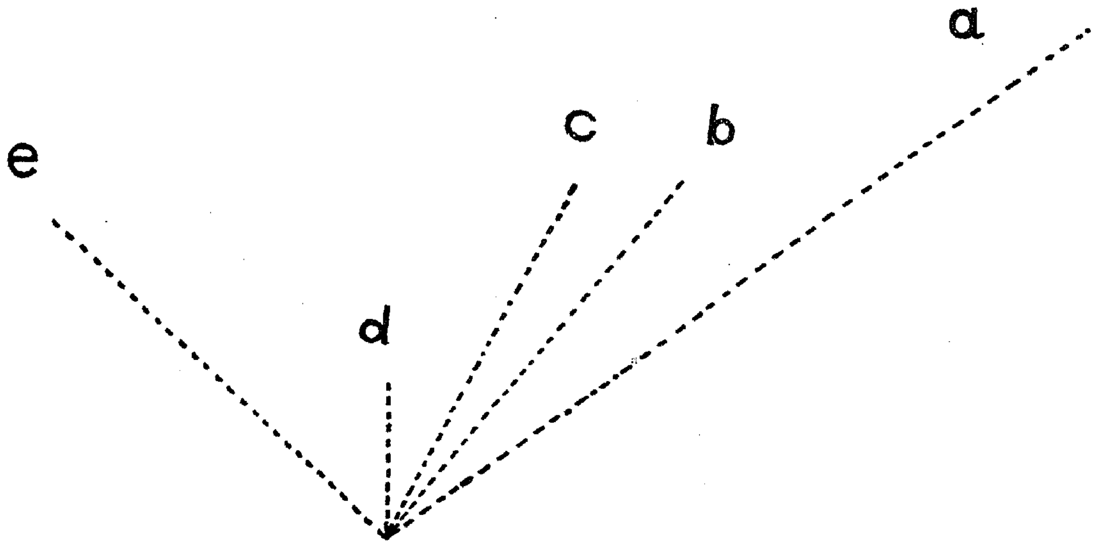

FIG. 1.

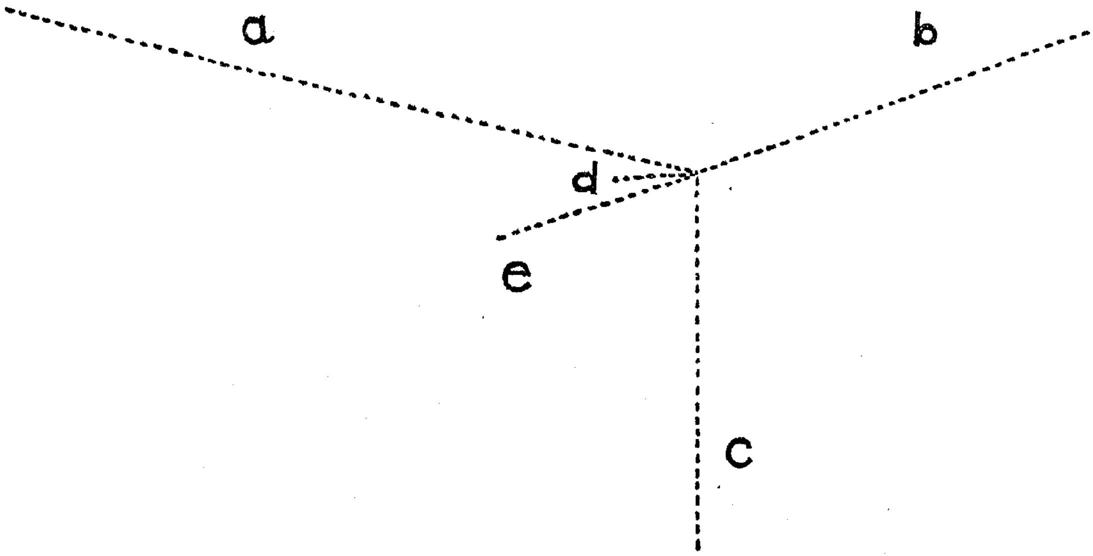

FIG. 2.

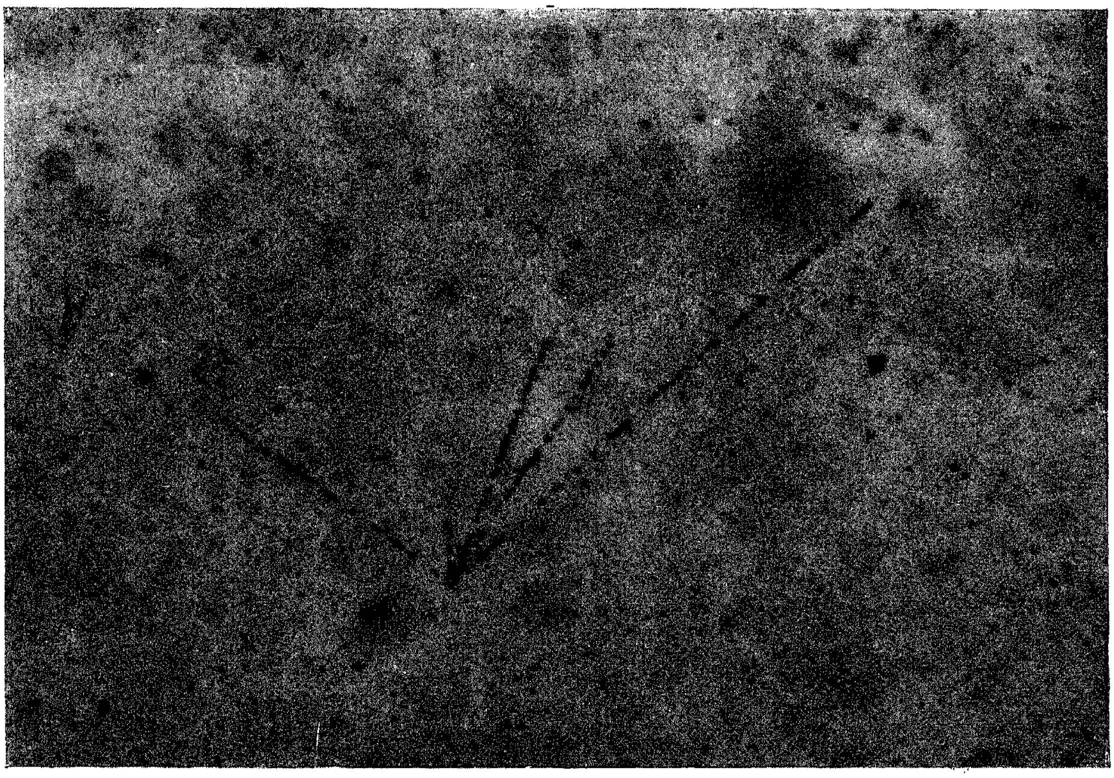

FIG. 3. Magnification ×1135