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SOME PHYSIOLOGICAL EFFECTS OF RADIUM RAYS[1]

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It is probable that no scientific discovery, since the publication of Darwin's "Origin," has so revolutionized our conceptions of natural phenomena as has the discovery of radioactivity by Henri Becquerel, and of radium, by M. and Mme. Curie and Bémont. In the light of these epoch-making discoveries we have completely revised our concepts of the nature of matter and of electricity. The atom, the "undivided," has been shattered into fragments, and a large percentage of the investigations in the realm of physics and chemistry now have to do with atomic disintegration and the behavior of the resulting products.

It was Rutherford and Soddy who first proposed the hypothesis that radioactivity is a manifestation of the disintegration of atoms, and this hypothesis, chiefly through the investigations of Rutherford, has already assumed the rank of a theory.

It would be superfluous to enter here into a detailed account of the nature of radioactivity, as understood at present. Suffice it to say that the theory elaborated by

[1] The investigations embodied in this paper are treated more fully in the author's memoir on "Effects of the Rays of Radium on Plants" (*Mem. N. Y. Bot. Garden*, 4. Sept., 1908). It has not been thought desirable to enter into a discussion here of previous researches on the subject, since the literature is fully treated in the memoir. It is a pleasure again to express my indebtedness to Mr. Hugo Lieber, of Lieber & Co., New York City, whose great liberality in supplying all the radium made the investigation possible.

Rutherford involves a conception of the atom as a body composed of intricately related units. These units possess relatively enormous amounts of kinetic energy, and are in rapid orbital motion within the atom. In some substances of high atomic weight, such as uranium, polonium and radium, these units spontaneously escape from the atom and fly off into space. Such substances are called radioactive, and the emission of these units is radioactivity.

The particles themselves are called ions. They are of at least two kinds; one, called the β particles, very small (about one one-thousandth the size of a hydrogen atom), bearing a charge of negative electricity, and moving with a velocity approaching that of light; the other called α particles, about twice the size of a hydrogen atom, bearing a positive electrical charge, and moving at a much lower velocity than the β particles. The β particles or negative ions are called electrons.

Streams of negative electrons constitute the so-called β rays; streams of positive ions the α rays. Both α and β particles move with velocities that vary between certain limits and so the respective rays are complex.

In addition to the giving off of α and β rays, radioactivity involves the emission of electro-magnetic pulses in the ether. These are analogous to very penetrating X rays, and are called γ rays.[2]

The enormous velocity of the β particles, combined with their inconceivably small size, renders them very penetrating. They pass readily through matter opaque to light, moving between the molecules, or even passing directly through the latter, being smaller than the spaces by which the atoms are separated within the molecule. In their passage through substances they may collide with and so dislodge other electrons, thus producing ionization. The α particles, owing to their larger size

[2] Jean Becquerel (*Compt. Rend. Acad. Sci. Paris,* **146**: 1308. 22 Je 1908, **147**: 121. 13 Jl, 1908) reports the experimental demonstration of the existence of free *positive* electrons, but whether such electrons are involved in radioactivity has not been determined.

and lower velocity, are less penetrating than the β particles, but are much more effective ionizers. The γ rays behave as X rays.

In addition to the three types of rays above described, radioactive substances are the source of a heavy, inert gas, belonging to the argon family. This gas, named by Rutherford the emanation,[3] is itself radioactive, giving off only α rays.

Studies of the physiological effects of radium, therefore, must take into consideration the three types of rays, described above, and also the radioactive gas, the emanation. In the experiments recorded below, the radium, in the form of radium bromide, was contained in sealed glass tubes, or employed as a thin coating on a suitable surface. In the former case only X and γ rays were available, as the α rays and the emanation can not pass through the walls of the tubes. In the latter case the α rays together with the emanation were also available.

The effects of radium upon plants have been investigated by Dixon and Wigham[4] in Great Britain, by Koernicke[5] in Germany, by Guilleminot[6] in France, and by several others. Without going into the details of their work it may be stated that the general conclusion from their experiments is that the rays exert either a retarding or an inhibiting effect on physiological processes. Koernicke, however, found some evidence that acceleration of activity might follow exposure to the rays under suitable conditions.

My own investigations have led to the conviction, already reported,[7] that radium rays act as a stimulus to

[3] The use of the plural "emanations" to designate all the rays and influences coming from radium, has been somewhat common in biological papers. It has no warrant, is only confusing, and should be abandoned.

[4] *Nature,* **69**: 81. 1903. *Proc. Roy. Dublin Soc. Sci.,* N. S., **10**^{2}: 178. 1904. *Notes Bot. School, Trinity Coll.,* Dublin, **1**: 225. 1905.

[5] *Ber. Deut. Bot. Ges.,* **22**: 148, 155. 1904; **23**: 324, 404. 1905.

[6] *Compt. Rend. Acad. Sci. Paris,* **145**: 711. 1907; *Compt. Rend. Assoc. Française Adv. Sci.,* **36**^{1}: 389. 1907; **36**^{2}: 1344. 1908; *Compt. Rend. Acad. Sci. Paris,* **145**: 798. 1907.

[7] "Effects of the Rays of Radium on Plants." New York, 1908. (*Mem. N. Y. Bot. Garden,* Vol. IV.)

plants. If this stimulus ranges between a minimum and an optimum point an excitation of function results; if beyond the optimum point a depression of function, passing to complete inhibition as the strength or duration of the treatment is increased beyond the point of optimum stimulation. The following experiments are chosen from nearly 200, and indicate the nature of the evidence upon which the above conclusions are based.

Eight dry seeds of the bean (Phaseolus—Henderson's "Long Yellow, Six Weeks") were placed in moist sphagnum with their hilum-edges touching a rod coated with a Lieber's radium-coating[8] of 10,000 activity.[9] After

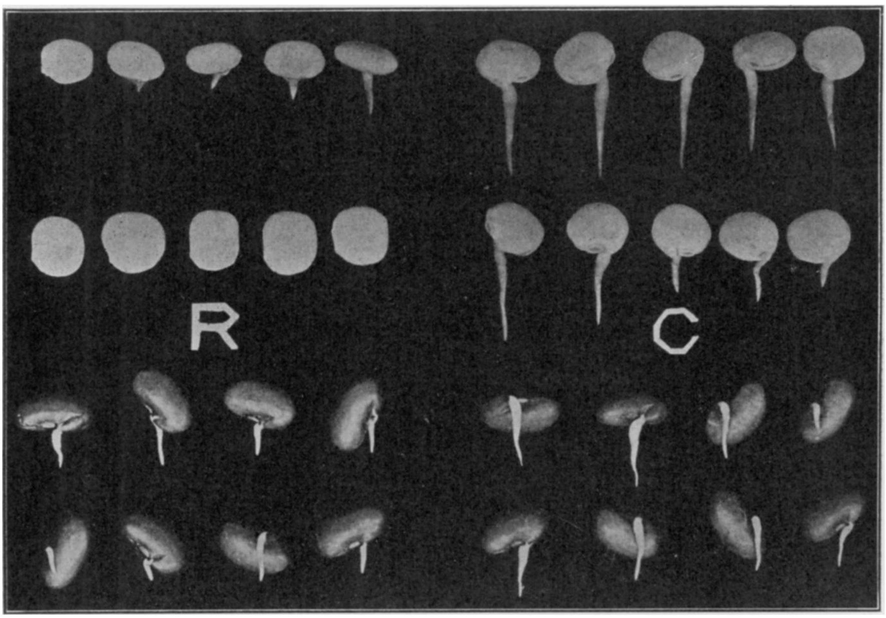

FIG. 1. Effect of radium rays on the germination of *Lupinus albus* and *Phaseolus*.

three days (70 hours) exposure, the radicles of the exposed seeds averaged 13.18 mm. in length, those of a control set 15.12 mm. Ten dry seeds of *Lupinus albus* were similarly exposed to a coated rod of 25,000 activity and,

[8] See Gager, *l. c.*, Chapt. VI.

[9] The unit of activity is the activity of uranium. Radium of, *e. g.*, 10,000 activity is 10,000 times as active as uranium.

at the end of three days (70 hours) the radicles of the exposed seeds averaged 3.81 mm. in length, those of the control set 21.80 mm. The retardation of germination and growth following this treatment is illustrated in Fig. 1.

A row of timothy grass seed (*Phleum pratense*) was sown on a moist blotter. Over the center of the row was suspended vertically a sealed glass tube containing 10 mg. of radium of 1,500,000 activity in the end of the tube nearest the seeds. The distance from the tube to the seeds was about 5 mm. A second row was also arranged as a control (not exposed to radium). At the end of eleven days the control seedlings were all of about the same height and color (normally green) and averaged 30 mm. in height. The exposed plants were entirely etiolated directly under the radium tube and for a radius of 4 mm. on each side. The height of the seedlings gradually decreased from 30 mm. (average) at the

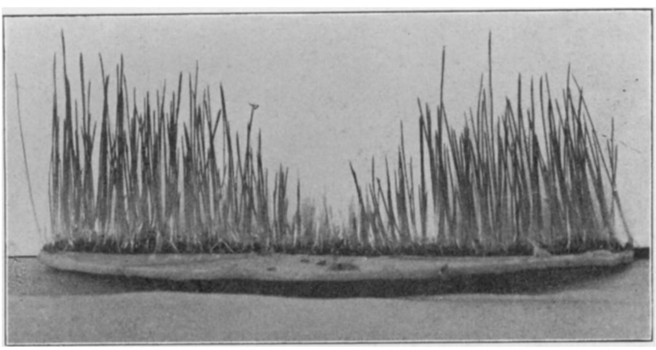

FIG. 2. Effect of radium rays on the germination and growth of timothy grass.

ends of the row, to 3 mm. at the center under the radium (Fig. 2).

Twenty seeds of "Lincoln" oats (Avena), with the glumes removed, were placed in two parallel rows with the radicle ends touching, and the embryo-side uppermost. Over them was laid the sealed glass tube of radium bromide of 1,500,000 activity, resting on the radicle ends of the seeds. After an exposure of 6 days and 15 hours, these grains, together with twenty similar but unexposed ones, were planted in flower pots in soil. The control grains germinated two days sooner than those exposed, and, at the end of seven days after planting, the seedlings from the exposed grains were just appearing above the soil, while the control plants were several centimeters tall (Fig. 3).

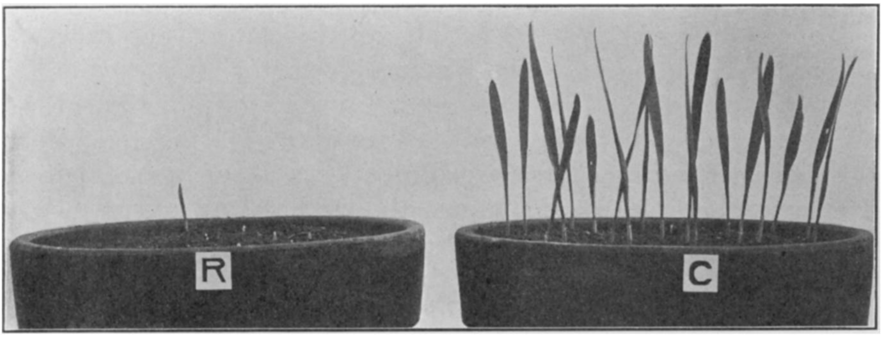

FIG. 3. Effect on the germination and growth of oats of exposing the grains before planting. Cf. Fig. 4.

In order to test the effect on germination and growth of radium rays in the soil, 16 unsoaked grains of "Lincoln" oats were sown in soil in a flower pot, in 3 concentric circles, at distances of 7 mm., 22 mm. and 45 mm. from the center of the pot. At the center

FIG. 4. Acceleration of germination and growth of oats by placing a sealed glass tube of radium in the soil (R). The tube in C is empty. Cf. Figs. 3 and 5.

the sealed glass tube of radium (1,500,000 ×) was inserted vertically into the soil, with the end containing the radium at a depth of about 5 mm. below the surface. A control culture was similarly arranged with an *empty* glass tube. After an exposure of 106 hours the seedlings in the pot containing the radium were all up, and were most decidedly taller than those in the control culture, three of which were not yet up, and all of which were less developed in every way than those exposed to the radium.

The plants in the outer circle of the exposed culture averaged 50 mm., those in the middle circle 46 mm. and those in the inner circle 42 mm. taller than those in the corresponding circles of the control (Fig. 4).

On the sixth day after planting the radium tube was changed to the control culture, and the empty tube replaced the radium. The pot C was then irradiated (CR)

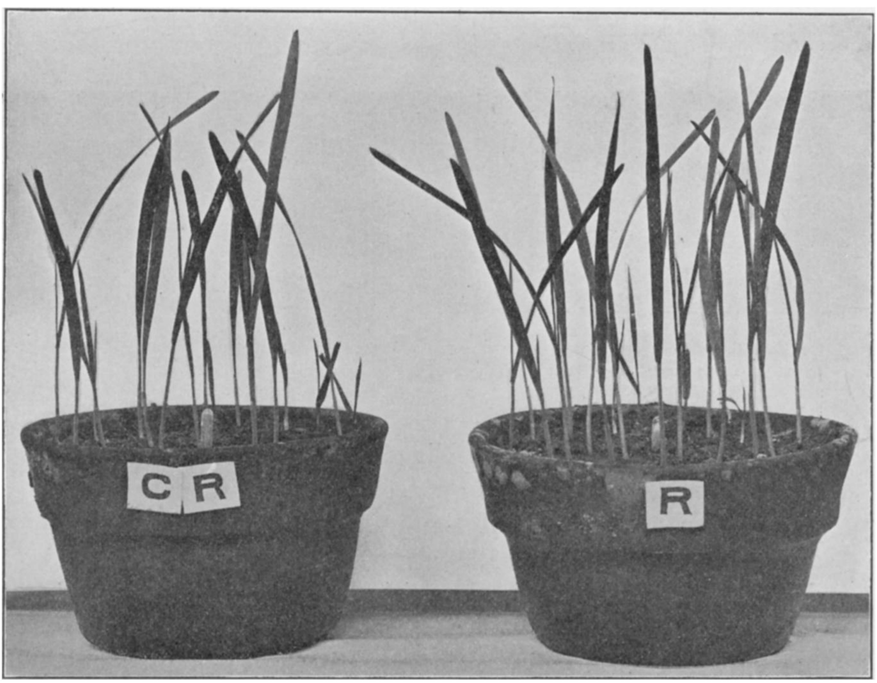

FIG. 5. The same cultures as those shown in Fig. 4, six days later. The radium tube is now in C (CR), and R serves as the control. Cf. Fig. 4.

and R became the control. At the end of five days after this change the plants in CR (Fig. 5) were nearly as tall as those in C and the exposure was photographed. Eventually the plants in CR exceeded those in R, and thus, by changing the radium tube from one pot to the other, the growth of either culture could be accelerated at will.

In order to ascertain the effect on growth of exposing seeds for the same length of time to radium of various degrees of activity, three sets, A, B and C of six dry seeds each of *Lupinus albus* were exposed to rays from radium in sealed glass tubes by laying the tubes against the hilum-edges of the seeds. The duration of exposure was 91.5 hours, and the strengths of the radium as follows: A, 1,800,000 ×; B, 1,500,000 ×; C, 10,000 ×; D, control, not exposed. At the close of the period of exposure the seeds were planted in soil, each set in a different pot. The experiment was photographed eleven days after the seeds were planted (Fig. 6), and curves of growth of the

FIG. 6. Effect on growth of exposing seeds of *Lupinus albus* for 91.5 hours to rays from radium of various degrees of activity. From left to right the activity was 1,800,000; 1,500,000; 10,000; C, control. Cf. Fig. 7.

four cultures are shown in Fig. 7. It is seen at a glance that the effect of the rays on growth varies directly with the degree of activity of the radium. The apparently anomalous rise of the 1,800,000 curve during the first days record (Fig. 7) is due either to poor exposure of some one of the seeds of that culture, or represents an individual variation in resistance to the rays that was not compensated for because of the small number of seeds necessarily employed.[10]

To show the effect of duration of exposure to radium of the same activity, four sets of six dry seeds each of *L. albus* were taken. Three of them A, B and C, were exposed as follows to the rays from 10 mg. of radium

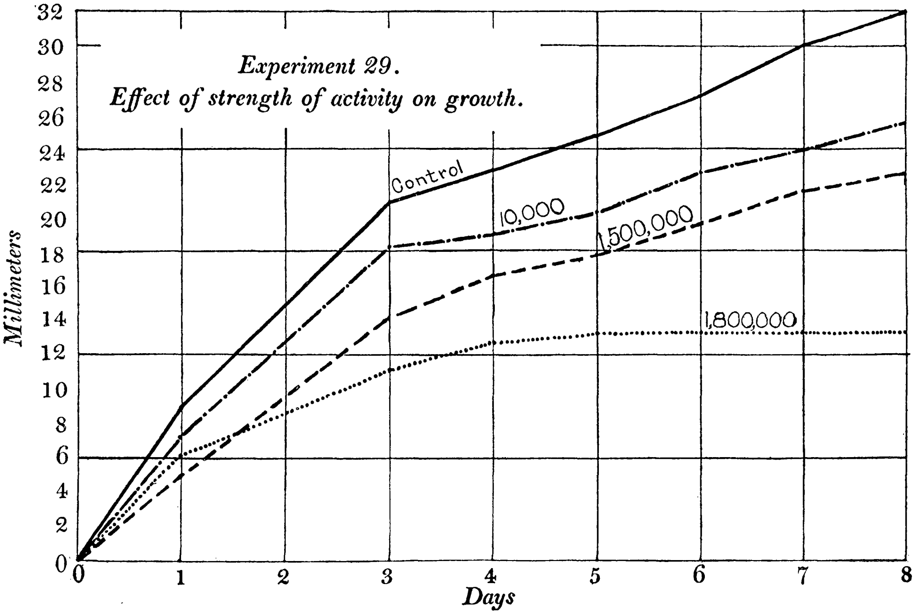

FIG. 7.

bromide of 1,800,000 activity, in a sealed glass tube: A, 72 hrs.; B, 50 hrs.; C, 26 hrs.; D, control, not exposed. The seeds were then planted, without soaking, in separate pots of soil. At the end of 5 days the average heights of the seedlings above the surface of the soil were as follows: A, 88 mm.; B, 95 mm.; C, 134.50 mm.; D, 145 mm. Inspection of the curves of growth for the four cultures (Fig. 8) shows that, for a given activity of radium, the effect on growth varies directly with the duration of the exposure.

The retardation of starch formation by a green leaf in the light was shown as follows. A nasturtium (*Tropæolum*) plant was removed to the light after being in darkness for 18 hours. Under one of the leaves,

[10] The length of the tube did not permit of satisfactorily exposing a larger number of seeds at one time.

empty of starch, was placed a Lieber's radium-coated rod of about 25,000 activity. The rod was placed under the leaf in order not to shade the latter. After an exposure of twenty-four hours the leaf was decolorized and tested with iodine. Abundant starch was found on the edge of the leaf farthest from the rod, but only very slight

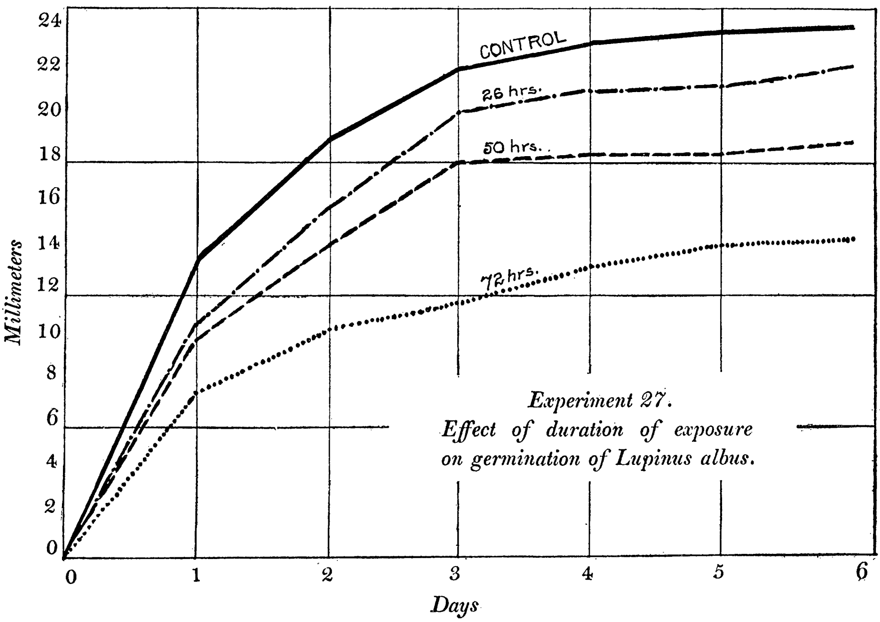

FIG. 8.

traces elsewhere, especially in the region that was directly over the rod. A print of the leaf was made by laying it over a sheet of velox paper in a printing frame and exposing it to light. In this way the portions having less starch, and, therefore, more transparent, showed darkest on the print (Fig. 9).

All attempts to demonstrate a direct tropistic response to the rays, by either roots or shoots, were unsuccessful. When, however, a sealed glass tube containing about 50 mg. of radium bromide of 10,000 activity was suspended horizontally in a culture solution, at a distance of from 2–10 mm. from the root-tips of *L. albus,* the roots curved toward the tube (Fig. 10). In an experiment in which a culture solution was substituted for the tap-water, the angle of curvature was more abrupt (nearly 90°). It seems probable that this is an indirect response, due to the effect of the radium rays on the water or solution.

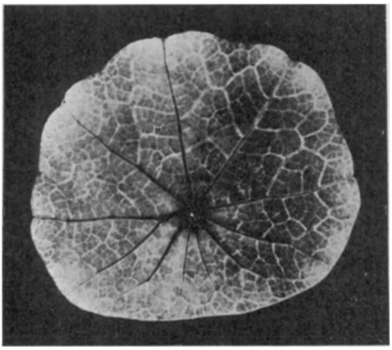

FIG. 9. Retardation of photosynthesis by radium rays. A direct heliograph, made by interposing the leaf between velox paper and the light. The darker portion represents the region exposed to the rays.

FIG. 10. Curvature of root-tips toward a sealed glass tube of radium bromide (10,000 ×) in a culture solution.

Whether the rays increase the number of ions of an electrolyte in solution is still a debated question,[11] but the physiological effects of tap-water exposed to the rays seem to leave no doubt but that the latter alter a solution in some way. How, we do not know.

Micheels and de Heen[12] were among the first to study the effect of the rays on plant respiration. Under the conditions of their experiments respiration was always retarded. In one of my own experiments, soaked grains of wheat (*Triticum*) weighing, when dry, 2 gm., were supported on a moist blotter in a tumbler over a saturated solution of KOH. Over the wheat, and in contact with the grains, was placed the sealed glass tube of radium of 1,500,000 activity. The CO_2 given off by the wheat was absorbed by the KOH, and the consequent rise of mercury in a graduated tube of small bore was taken as an index

[11] Cf. *Mem. N. Y. Bot. Garden,* **4**: Chapt. XIX. 1908.

[12] *Bull. Acad. Roy. de Belgique Class. Sci.*, p. 29. 1905. *Bot. Cent.,* **98**: 646. 1905.

of the rate of respiration. Under such conditions, and with radium of 10,000 as well as 1,500,000 activity, the result was always an acceleration of respiration, as is shown in Fig. 11. It is probable that, under certain con-

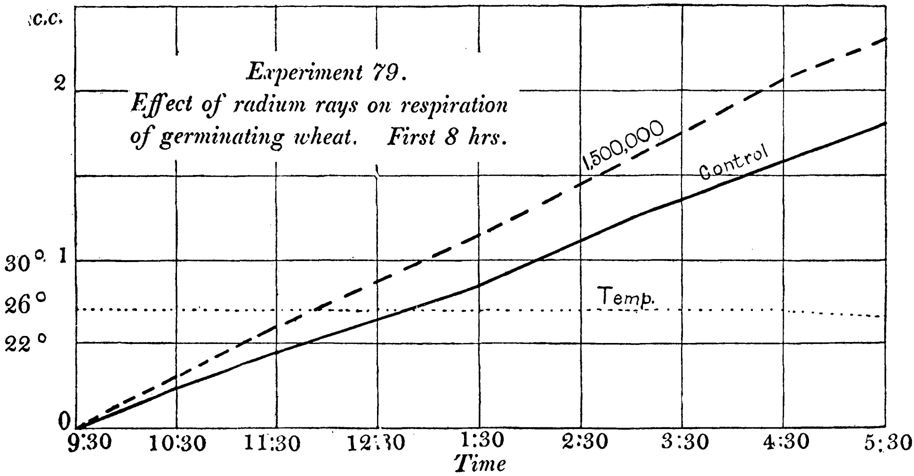

FIG. 11.

ditions of exposure, the rays would retard or completely inhibit respiration.

In order to test the influence of the rays on alcoholic fermentation, mixtures of commercial yeast in ferementation tubes were exposed to the rays. A piece of compressed yeast weighing 1 gm. was thoroughly mixed in 100 c.c. of tap-water, and equal portions of this mixture were placed in fermentation tubes. Into these tubes were placed sealed glass tubes containing radium bromide of activities 7,000, 10,000 and 1,500,000. A fourth fermentation tube with no radium served as a control. The rate of fermentation was measured by the rate of evolution of the gas. The results of all experiments indicated a decided acceleration of fermentation under the influence of the rays, and, as the curves in Fig. 12 clearly show, the amount of acceleration is in direct proportion to the activity of the radium.

No reference has yet been made of the fact that radioactivity is a factor in the normal environment of plants.

I have elsewhere[13] noted this, and have presented[14] a mass of evidence from the realm of physical science indicating the general distribution of radioactivity. It exists in air and soil, in spring-water, and in freshly fallen rain and snow. Potassium, one of the essential elements of

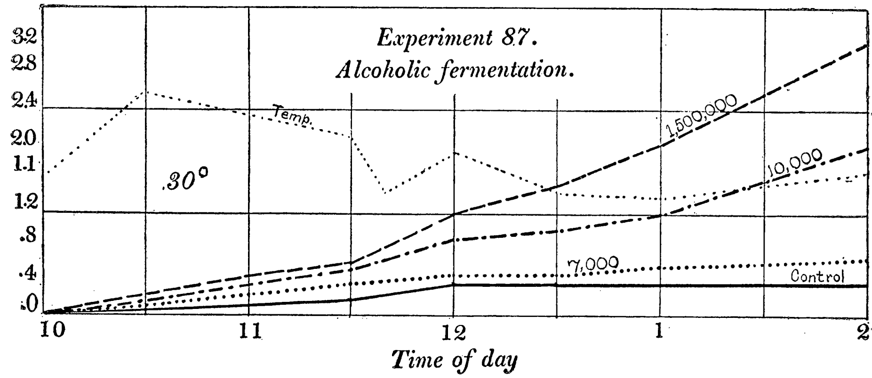

FIG. 12. Acceleration of alcoholic fermentation by radium rays.

plant food, has been found by Campbell to give off β rays,[15] and some evidence has also been found that calcium possesses the same property. The researches of many investigators have clearly demonstrated the general occurrence in nature of free negative electrons. These discoveries not only add to the interest and importance of the study of the physiological rôle of radium rays, but also point out the way for further investigation.

An arrangement devised by Mr. Hugo Lieber facilitated the study of the effect of a radioactive atmosphere on germination and growth. The apparatus is clearly shown in Fig. 13, and needs little further explanation, except to say that the hollow cylinder, R, has its inner surface coated with a Lieber's radium coating. The bell-jars fit tightly on to the ground glass plates, and a current of air is kept passing through the jars by attaching the tubing from the lower tubulure to an exhaust pump. The air passing through the radium-lined cylinder carried with it the emanation given off by the

[13] *Science*, N. S., **25**: 263. 1907.

[14] *Mem. N. Y. Bot. Garden*, **4**: Chap. II. 1908.

[15] *Proc. Cambridge Phil. Soc.*, **14**: 211. 1907. *Nature*, **76**: 166. 1907.

radium, and thus the plants were subjected chiefly to the influence of α rays.

In the experiment here described, dry seeds of timothy grass were sown on the surface of the soil in two pots

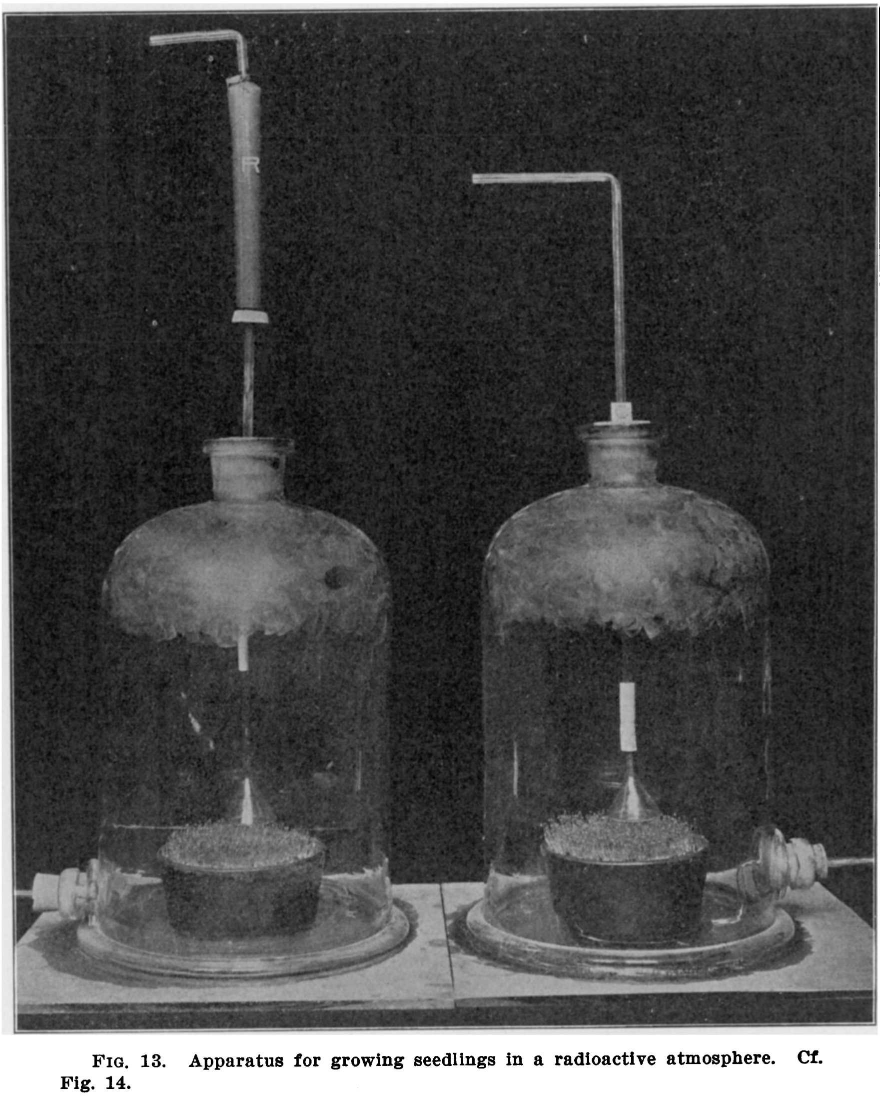

FIG. 13. Apparatus for growing seedlings in a radioactive atmosphere. Cf. Fig. 14.

and placed, one under each of the bell-jars. After five days, during which a continuous current of air was delivered over the cultures, the seeds were found to have germinated and grown uniformly under the control jar, but, in the culture exposed to the emanation, the seeds immediately under the funnel through which the emanation was delivered had entirely failed to germinate. The other seedlings of this culture were only very slightly less vigorous than those of the control (Fig. 14).

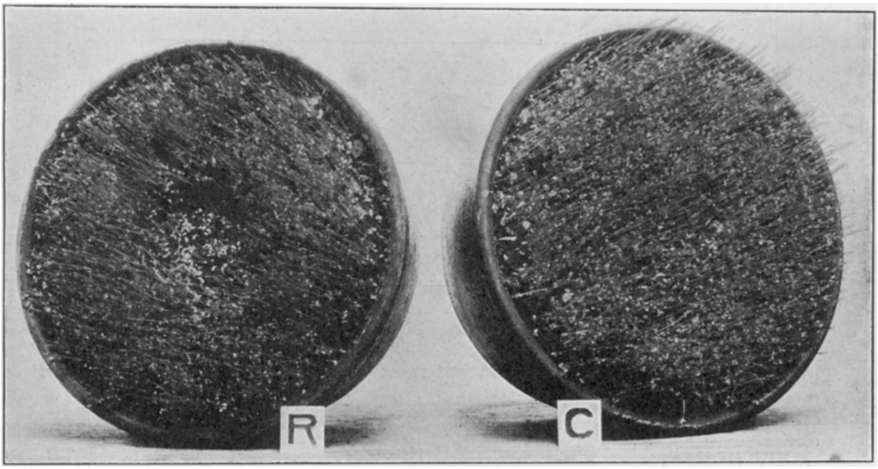

FIG. 14. Result of growing timothy grass in a radioactive atmosphere as shown in Fig. 13, R, exposed cultures; C, control.

To further investigate the effects of this radioactive air, five germinated seeds of *L. albus* with radicles over 10 mm. long were marked with India ink 10 mm. back from the root-tip. These seedlings were then suspended vertically, five under each bell-jar. The air, normal in one jar, radioactive in the other, was forced into the bell-jars by means of a rubber bulb, the blasts being given at irregular intervals of from two to twenty-four hours. At the end of the first twenty-four hours the average length of the exposed radicles was 19.00 mm., and of the control only 12.10 mm. At the end of the second twenty-four hours the average lengths were, for those exposed 23.30 mm., for those unexposed, 12.70 mm. The curves of growth for this experiment are given in Fig. 15, showing the acceleration in rate of growth under the conditions imposed.

The growth of roots was retarded in water exposed for twenty-four hours to the rays. The experiment was made as follows: Into 100 c.c. of tap-water, in which sealed glass tubes of radium bromide had lain for twenty-

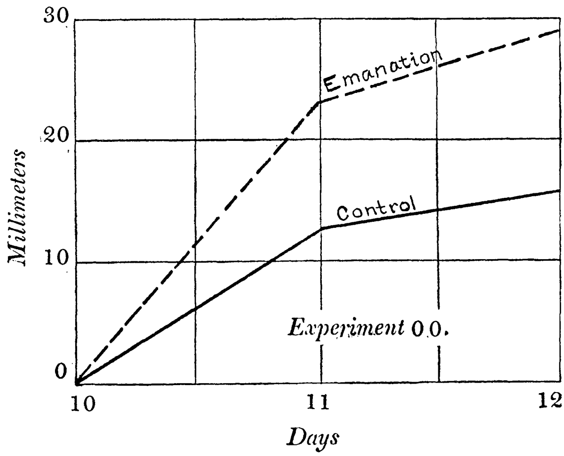

FIG. 15. Acceleration of growth of roots of *Lupinus albus* in a radioactive atmosphere.

four hours, the radicles of four germinated lupines were suspended up to an ink mark, placed 10 mm. back from the root-tip. Three cultures were arranged: A, with radium of 1,800,000 activity; B, with radium of 1,500,000 activity; and C, with no radium, serving as a control. At the end of five days the average lengths of the hypocotyls were, for A, 79.62 mm.; for B, 85.50 mm.; for C, 117.75 mm. The result, then, was a retardation of growth, in direct proportion to the degree of activity of the radium to which the water was exposed (Fig. 16).

Following up the suggestion in the discovery that freshly fallen rain is radioactive, several experiments were made with a view of ascertaining the effect of this radioactivity on plant growth. Rain-water was caught in the open, in chemically clean glass dishes, after about four hours of rain, so that the air was well washed. This water was kept carefully covered, for one month, when another opportunity presented itself of collecting another lot of rain under similar favorable circumstances. The experiment was set up immediately after the last collection, using radicles of *Lupinus albus,* immersed to a measured length of 5 mm. in both the fresh and the stale water. Two parallel experiments, A and B, were run,

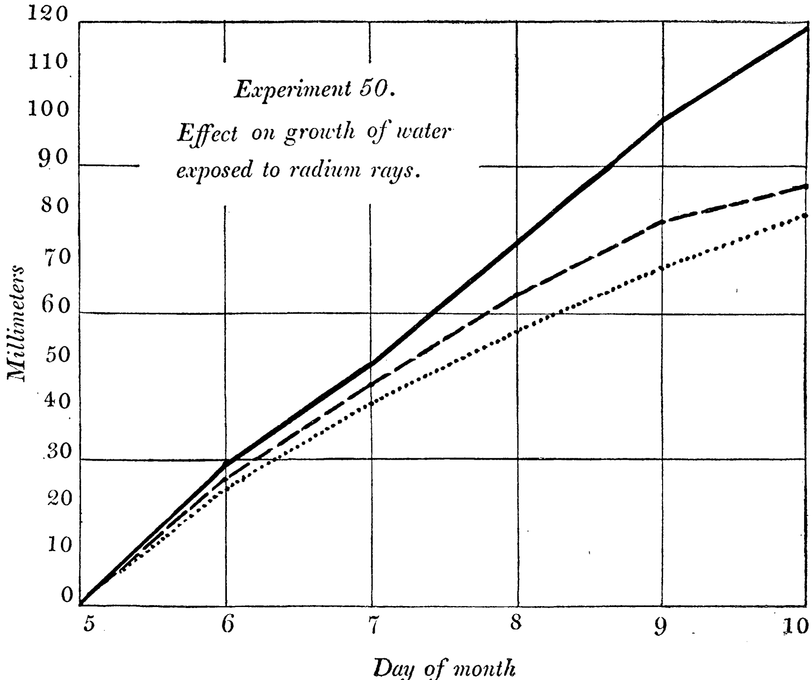

FIG. 16.

each with a "fresh" and a "stale" culture. At the end of 48 hours the lengths of the radicles averaged, for set A, 23.50 mm. fresh; 27.50 mm. stale: for set B, 22.38 mm. fresh; 27.00 mm. stale. The curves of growth are shown in Fig. 17. The experiments of which this is a type indicate that, as a result of its radioactivity, freshly fallen rain water tends to retard the growth of roots. We have as yet no data on the effect of this factor on the activities of the shoot.

Profound histological changes follow exposure to the rays. These effects are due chiefly to a disturbance of the normal functioning of the cambium, and are in harmony with results of experiments on animals, in which it has been shown that embryonic tissue is more sensitive than any other. After an exposure of seeds under certain conditions, the cambium is frequently entirely lacking, all of the cells in the given organ having passed over into the mature state. The treatment appears to accelerate the approach of senescence.

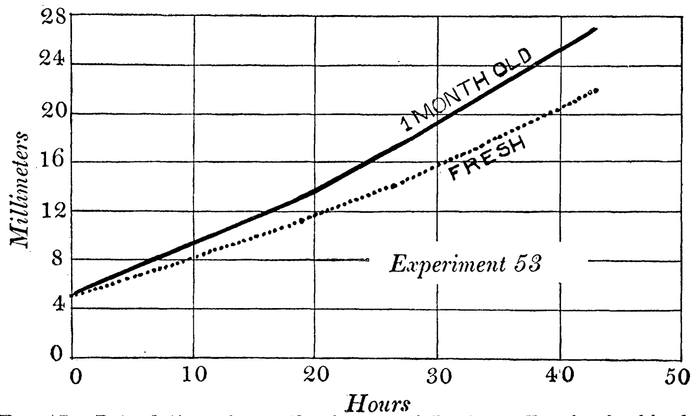

FIG. 17. Retardation of growth of roots of *Lupinus albus* by freshly fallen rain water. Cf. Fig. 16.

Exposure to the rays also induces marked irregularities in mitosis. This is shown, among other ways, by the failure of some of the chromosomes to take part in the organization of the daughter nuclei. Usually such chromosomes organize smaller, nuclear-like structures within the daughter-cells. In one instance they were observed to be undergoing an independent karyokinesis at one side of the main mitotic figure. Interesting possibilities are here suggested, along the line of experimental mutation.

Experiments like those described in this paper have been many times repeated with confirmatory results, and seem amply to justify the general conclusion, earlier stated, that radium rays are a stimulus to plant activities. The reaction to a stimulus between the minimum and optimum points is an excitation, or acceleration of the given process; the reaction to an over (superoptimal) stimulus is a depression, or retardation of function, and, if the stimulus is sufficiently intense, complete inhibition or ultimate death.