It is interesting to note in this connection that the low temperature modification of liquid helium[19] has an unmeasurably small viscosity.[20] Since helium does not solidify unless it is compressed it is reasonable to assume that it is kept in the liquid state because of the zero-point vibrations of the atoms[21] which, for helium, are comparable with the heat of evaporation. The experiments on the viscosity of helium indicate that in a "quantum liquid" the particles may rearrange without crossing potential barriers.

The absence of low lying rotational levels in heavy nuclei definitely indicates therefore that if nuclei are to be compared with a phase of matter in macroscopic experiments the correct analog to use is not a crystallite but a droplet of a "quantum liquid" such as the low temperature modification of liquid helium.

[19] W. H. Keesom and M. Wolfke, "Comm. Phys. Lab. Leyden," No. 190b.

[20] P. Kapitza, Nature **141**, 74 (1938); J. F. Allen and A. D. Misener, Nature **141**, 75 (1938).

[21] Simon, Nature **133**, 460 and 529 (1934); F. London, Proc. Roy. Soc. **153**, 576 (1935).

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New Experimental Evidence for the Existence of a Neutrino

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A new method is used for determining the energy of recoil of the nucleus in the individual beta-disintegration process. A gaseous compound of radiochlorine is placed in a cloud chamber. The clearing field is removed long enough before the expansion to allow the ions to spread out so that the resulting droplets can be seen individually. A cluster of droplets appears at the beginning of the track, and this is believed to be produced by the recoil nucleus. From the number of droplets an estimate is made of the kinetic energy of the nucleus, and this is compared with that calculated from the observed curvature of the beta-ray track. It is found that the laws of momentum as well as those of energy indicate that a third particle participates in the disintegration.

Introduction

In the experiment to be described[1] the momenta of both the electron and the recoil nucleus have been simultaneously measured for the elementary beta-disintegration process. This is the first experiment which has given any information at all regarding the momentum relations in the *individual* disintegration event. Although the results are of limited accuracy, they strongly indicate that momentum is not conserved between the electron and the nucleus alone. Hence the laws of momentum, as well as those of energy, indicate that a third particle participates in the disintegration.

The idea of observing the disintegration of a substance in the form of a gas in a cloud chamber has been suggested many times as a possible way of measuring the momentum or energy of recoil and the direction of recoil of the nucleus emitting the beta-ray. The difficulty with such a scheme is that the length of track made by the nucleus is far too short for observation, even in a cloud chamber operated at the lowest possible pressure. The nucleus will, however, produce a number of ion pairs concentrated in a very small region of space, and the number of ion pairs will be a function of the kinetic energy of the nucleus. It occurred to the authors that if these ions could be allowed to diffuse into a cluster several millimeters in diameter before the condensation were brought about, the individual droplets could be counted, and hence the kinetic energy of the nucleus could be estimated. It was found that this could be accomplished, and by applying a magnetic field to the chamber it was possible to know the momentum of the electron in each case, so that the estimated momentum of the nucleus could be compared with that of the electron.

[1] Halpern and Crane, Abstract 5, New York Meeting of the American Physical Society, Feb. 25–26, 1938.

Apparatus and Experimental Method

An automatic Wilson cloud chamber[2] 15 cm in diameter and 4 cm deep was used, which was filled with air at atmospheric pressure, ethyl alcohol vapor, and a trace of a gaseous compound of the radioactive material. In order to allow the ions to diffuse before the alcohol vapor was made to condense upon them, the clearing field was removed a fraction of a second before the expansion. This was accomplished by means of an adjustable contact in the automatic timing system. Two Sept 35 mm cameras, having f:3.5 lenses were placed 25 cm above the chamber and at a 30 degree angle to each other. This gave close-up views from two directions of only a part of the chamber. The tracks were illuminated by means of a carbon arc, flashed at about 200 amperes, and were photographed at 1/15 second exposure. A rectangular coordinate system of lines 3 cm apart was scratched on the lower surface of the glass top plate of the chamber. By measuring the apparent position of the beginning point of a track with respect to the lines on the plate in each of the views, an accurate determination of the distance of the point below the plate was possible. The two stereoscopic views were projected at the same time, but were not superimposed on the same screen. The position of a given point on a track relative to the coordinate system was simply recorded for each of the two views. Only those tracks which were found to begin at a point well within the illuminated portion of the chamber were included in the final data.

The radioactive material used in the first part of the experiment was radiochlorine, Cl^{38}, produced by bombardment of NaCl by 6 Mev deuterons in the University of Michigan cyclotron. This emits negative electrons with a half-life of approximately 37 minutes, and with an upper energy limit of about 5 Mev.[3] The combination of high energy, long half-life and fairly low atomic weight make this element suitable for our purpose. A gaseous compound of the chlorine suitable for introduction into the cloud chamber was made by the following procedure. The bombarded NaCl (a fraction of a gram) was put into a test tube containing about 5 cc of sulphuric acid, diluted 1 to 3, and a few grams of manganese dioxide. This produced free chlorine in solution. A few cc of ethylene dichloride were introduced into the test tube. This formed a layer above the sulphuric acid. Ethylene gas (generated by dropping ethylene dibromide upon zinc metal) was then bubbled through the liquid in the test tube. The ethylene combined with the chlorine in the lower layer, forming ethylene dichloride, which dissolved in the ethylene dichloride of the upper layer. After bubbling for about 15 minutes the upper layer was drawn off and was shaken vigorously with a large quantity of water in order to remove traces of sodium (which was also radioactive) and also traces of free chlorine and of sulphuric acid. The amount of radioactive ethylene dichloride introduced into the cloud chamber was just that which could exist in the vapor state at room temperature, which was several drops. Into the otherwise dry chamber just slightly more ethyl alcohol than necessary to saturate the volume was added, and the chamber was sealed up with air in it at atmospheric pressure. The presence of an excess of either of the liquids was avoided in order to insure that as large a fraction as possible of the radioactive compound would remain in the vapor state. The time taken for the chemical procedure and for clearing the cloud chamber was 30 to 40 minutes. Needless to say, only a minute fraction of the original activity of the NaCl appeared in the cloud chamber at the end of the procedure, but sufficient activity was always obtained if the NaCl was bombarded for about 5 minutes with 6 microamperes of deu-

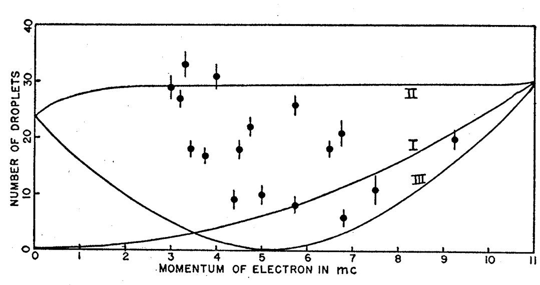

Fig. 1. Numbers of droplets produced by the recoil nuclei (corrected), shown in relation to theoretical predictions made on three different assumptions, as follows: curve I, no neutrino; curve II, neutrino and electron escape in the same direction; curve III, neutrino and electron escape in opposite directions.

[2] Crane, Rev. Sci. Inst. 8, 440 (1937).

[3] Kurie, Richardson and Paxton, Phys. Rev. 49, 368 (1936).

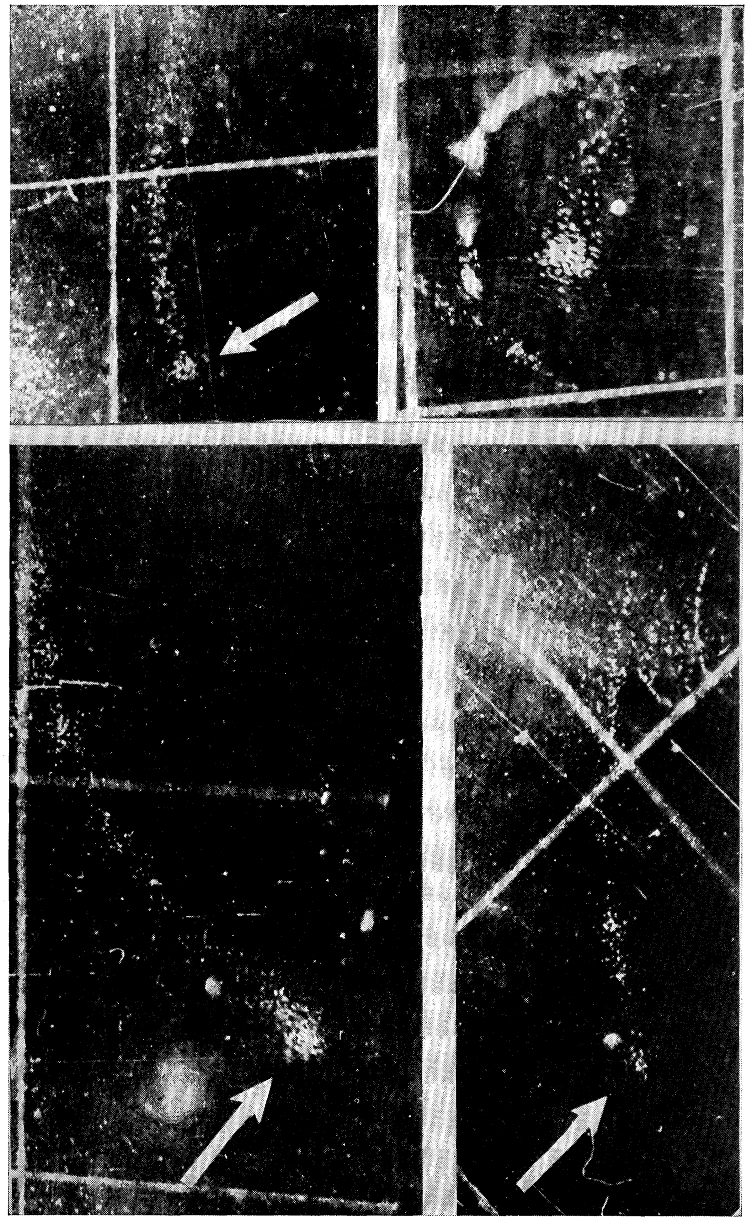

FIG. 2. Four different beta-ray tracks of intermediate energy, showing clusters of droplets at their beginning points.

terons at 6 Mev. The time of bombardment affords a convenient control on the final activity in the chamber, if the chemical procedure is standardized. From 200 to 300 photographs were taken with each loading of the chamber.

The gaseous compound of radiophosphorus[3] (P^{32}), which was used as the control in the second part of the experiment, was prepared as follows. Calcium phosphide (Ca_3P_2) was bombarded by 6 Mev deuterons in the cyclotron. This was decomposed by dropping water onto the solid Ca_3P_2 in an atmosphere of nitrogen. The resulting mixture of PH_3 and nitrogen was passed into the cloud chamber, which had already been flushed with nitrogen. The necessary amount of absolute ethyl alcohol was added,

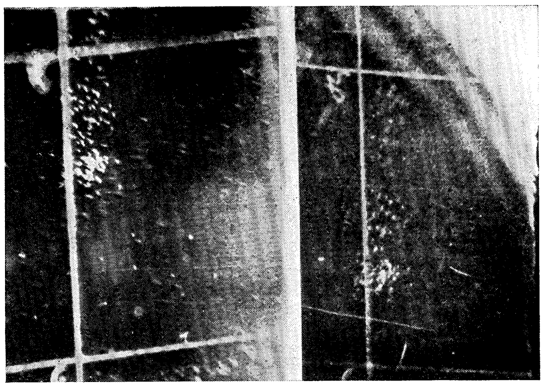

FIG. 3. An electron of high energy, in which the momentum of the electron is sufficient to account for the observed recoil of the nucleus. A stereoscopic pair of photographs is shown.

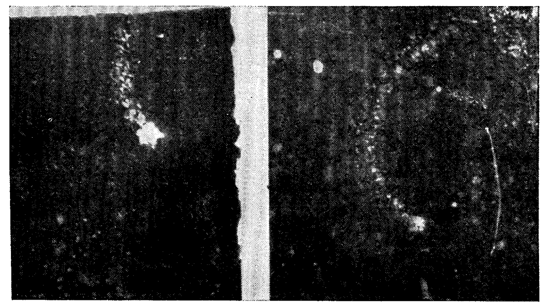

FIG. 4. Two separate tracks of low energy which are clear cases in which the nuclear recoil is larger than that expected from the electron momentum alone.

and additional nitrogen flushed through the chamber to reduce the activity to the optimum value. It was necessary to take precautions against having traces of oxygen present, because of its action on PH_3.

In determining the number of droplets to be assigned to the recoil nucleus, we made the simplifying assumption that the ions originating at a given point on a track diffuse in such a way as to fill with uniform density a sphere whose center is at the source and whose radius depends upon the time and speed of diffusion. On this assumption, the ions for which the recoil nucleus is responsible will fill a sphere of diameter equal to the width of the electron track. In the two-dimensional photograph a circle of this diameter is drawn around the nuclear cluster, the center of which is supposedly at the point of disintegration. The number of droplets inside the circle which are not due to the nucleus but to the electron can easily be calculated on the above assumptions to be nearly ρR, where ρ is the linear density of droplets along the electron track, and R is the radius of the circle. Accordingly we have subtracted ρR from the observed number of droplets in each cluster. ρ was determined by counting the droplets along several centimeters of the particular track. It is obvious that this correction, as it is here determined, is not dependent upon the track lying in a plane perpendicular to the direction of the camera: it is correct for any projection, provided ρ is determined in the same projection.

RESULTS

The results of the droplet counts on the 17 cases obtained with radiochlorine are shown as the dots in Fig. 1. No cases of electrons having less than 1 Mev energy are included, for a reason which will be given later in the discussion. The number of droplets produced by the electron within the region over which the droplets due to the nucleus extend, is subject to statistical fluctuation. To give an idea as to the amount of uncertainty due to this cause, a vertical line of length equal to $(\rho R)^{\frac{1}{2}}$ is drawn through each point. It is more difficult to estimate the uncertainty in the actual counting of the droplets, because this depends largely upon the quality of a given track. We estimate that this error ranges from 2 to 5 droplets.

In Figs. 2 to 4 are shown a number of the tracks obtained. Although all tracks were analyzed stereoscopically, both views are reproduced in only two of the examples. The ruled lines on the chamber top are visible, and are 3 cm apart.

The theoretical expectations for the number of ions produced by the nucleus were derived on three different assumptions. 1. That the momentum of the nucleus is equal to that of the electron (equivalent to assuming that there is no neutrino). 2. That a neutrino of zero or very small rest mass escapes in the same direction as the direction of flight of the electron, and that its momentum is $(W-E)/c$, where W is the upper limit energy of the beta-ray spectrum of Cl^{38} (taken as 5 Mev) and where E is the energy of the electron, calculated from its curvature in the magnetic field. 3. The same as 2 except that the electron and neutrino escape in opposite directions. In all the above calculations the kinetic energy of the nucleus was calculated from the momentum (its mass is known) and it was assumed that one ion pair (or two droplets) would be produced for each 30 electron volts of kinetic energy. The three possibilities are plotted in Fig. 1. It is clear that if all possible directions of emission of the neutrino with respect to that of the electron are considered, curves 2 and 3 will represent upper and lower limits for the number of droplets, and all the area between them will be permitted.

It is well known that a moving ion is able to produce other ions when its kinetic energy (in the moving coordinates of the collision) is only slightly above the ionization potential of the gas through which it is passing. But the question of the total number of ion pairs a heavy ion of a few hundred electron volts energy will produce before it comes to rest is difficult to answer. It would not be expected to produce more than the usual one ion pair per 30 ev, and could not under any circumstance produce more than one per 16.7 ev, which is the average ionization potential of air. On the other hand it could lose rather large fractions of its energy by thermal collisions without ionization. The numbers of droplets indicated by the points in Fig. 1 may therefore in some cases give too low values for the recoil momentum of the nucleus, but are less likely to give values which are too high.

Possibilities other than ionization by the recoil nucleus exist for producing ions in the neighborhood of the disintegrating atom. The escaping beta-ray may disturb the outer electronic structure of the atom, which may in its readjustment emit an electron of a few hundred volts energy, or may emit a soft x-ray quantum which will be absorbed in the immediate vicinity. To test this we carried out a control experiment, with radiophosphorus, P^{32}, instead of Cl^{38}. P^{32} is a good control because it has about the same atomic weight as Cl^{38}, emits negative electrons, but has a much lower upper energy limit. The greatest possible recoil energy for the P^{32} is 85 electrons volts, which should produce less than 6 droplets. Out of 25P^{32} disintegrations in the gas obtained, only two had detectable clusters of droplets at their beginning points. This negative result makes us feel certain that the clusters of droplets observed in the experiment with Cl^{38} were actually caused by the recoil of the nucleus.

Discussion

Meaning of the results obtained

It can be seen from the data presented that in the cases in which beta-rays of small momentum are emitted from radiochlorine the momentum received by the nucleus is usually much greater than that which it could have received from the beta-ray alone. This statement is not subject to any assumption about the efficiency of ionization by the nucleus: it is true even if we assume that the entire kinetic energy of the nucleus is utilized in ionization. This result has a bearing upon certain of the hypotheses which can be made as to the mechanism of beta-disintegration.

1. Suppose that the nucleus retains the excess energy temporarily, emitting it later by any means we may care to postulate. Momentum would then be conserved between the beta-ray and the nucleus, and the data would have to fall on curve 1, Fig. 1.

2. Suppose that the beta-ray carries off all the energy of disintegration, partly as kinetic energy and partly as extra mass, as has been suggested by the group in this laboratory,[4] by Jauncey,[5] and undoubtedly by others. Since the curvature of the beta-ray track in the magnetic field gives the momentum directly (assuming constant charge) the data in this case also would have to fall on curve 1, Fig. 1.

3. If the beta-ray spectrum owes its continuous distribution to a failure of the law of the conservation of energy, there is no reason to believe that the law of the conservation of momentum does not fail also. The present data are not able to eliminate this possibility. However, the experiment is inherently capable of throwing light upon the question if carried far enough, because if the above were true we should expect to find some cases in which the recoil momentum of the nucleus would be less than

[4] Breit, Rev. Sci. Inst. **8**, 141 (1937); Zahn and Spees, Phys. Rev. **53**, 524 (1937).

[5] Jauncey, Phys. Rev. **52**, 1256 (1937); Phys. Rev. **53**, 106 (1938); Phys. Rev. **53**, 197 (1938); Phys. Rev. **53**, 319 (1938).

the minimum which could be given to it by any combination of electron and neutrino energies or angles. Such cases would fall in the area below curve 3 on the right-hand side of the diagram in Fig. 1.

Of all the possibilities mentioned, the hypothesis that a neutrino is emitted simultaneously with the electron seems to fit the data best.

Lower energy component in the Cl^{38} beta-ray spectrum

Kurie, Richardson and Paxton[3] investigated the beta-ray spectrum of chlorine after bombardment with deuterons and found that it could be resolved into two components of about equal intensity and of K. U. upper limits 6.1 and 1.5 Mev. The actual observed upper limits, which we prefer to use in connection with our experiment, are about 5 and 1.2 Mev. They also found that gamma-rays of 2.4 and 1.9 Mev were emitted. The most reasonable assumption seems to be that the 1.2 Mev beta-ray spectrum and the gamma-rays are associated, since the sum of the energies, $1.2+2.4+1.9=5.5$ Mev, is about the same as the energy of the other beta-ray component. It is therefore reasonable to say that no gamma-rays are associated with the 5 Mev beta-ray component.

In our experiment we must be careful to include only those disintegrations which belong to the 5 Mev component, if we are to compare the results with the predicted recoil momenta. An electron which belongs to the 1.2 Mev spectrum, emitted practically simultaneously with the two gamma-ray quanta might give considerable recoil to the nucleus, but would tell nothing about the neutrino. We have therefore included in our data only those cases in which the electron has more than 1 Mev energy; it is fairly certain that these belong to the 5 Mev spectrum.

Use of other gases and radioactive substances

The use of hydrogen in the cloud chamber instead of air would decrease the linear density of ionization of the electron track, which would be an advantage, in that it would decrease the number of droplets to be subtracted from the nuclear cluster. On the other hand the droplets would fall faster, make sharp photography more difficult, and, most important of all, the number of ions produced in hydrogen by the nucleus would probably be much smaller than in air. In the collision of the recoil nucleus (A^{38} after the disintegration) with H_2, the kinetic energy of the A^{38} in the moving coordinates of the center of gravity of the system would be very small indeed, and ionization might not result. It is therefore better to use a gas of atomic weight comparable to that of the Cl^{38}.

The use of He^6 as the radioactive material would give a much greater recoil energy, because the upper limit of its spectrum is about the same as that of Cl^{38} and its mass is much smaller. He^6 has a half-life of 1 second, which means that it would have to be introduced into the chamber before each expansion. It would be difficult to maintain ideal conditions in the chamber under these circumstances, but perhaps not impossible.

Direction of emission of neutrino

The present experiment is inherently capable of giving the distribution in angle of emission of the neutrino with respect to the direction of emission of the electron. An accurate knowledge of the recoil momentum and the electron momentum would make it possible to solve for the angle in each case. Before the results can be interpreted in this way we must obtain exact information as to the efficiency of ionization by slow ions. The higher recoil energy of He^6 would lessen this difficulty.

ACKNOWLEDGMENTS

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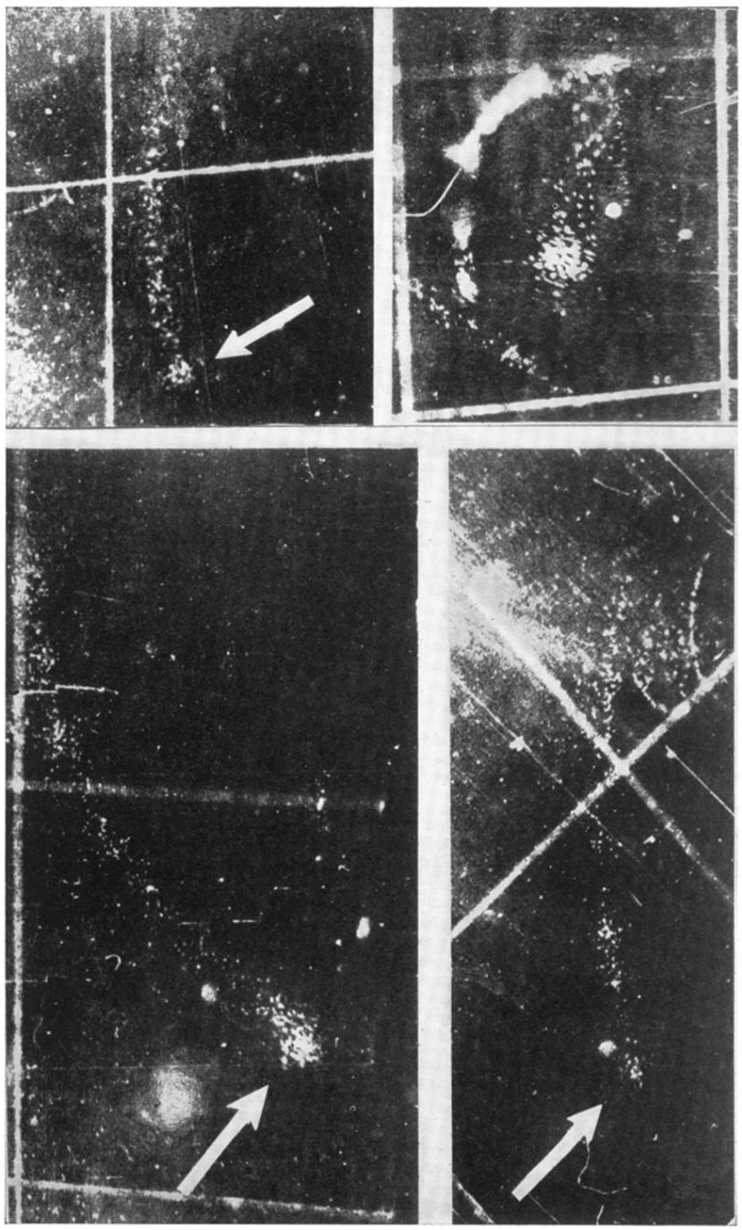

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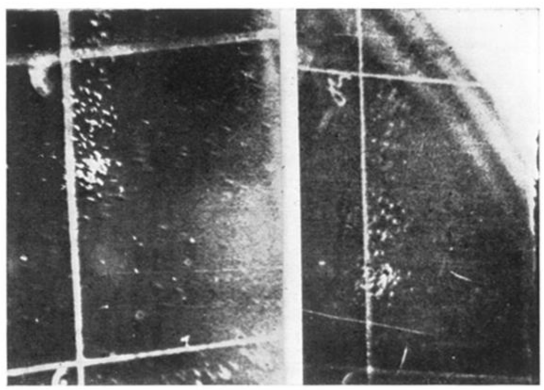

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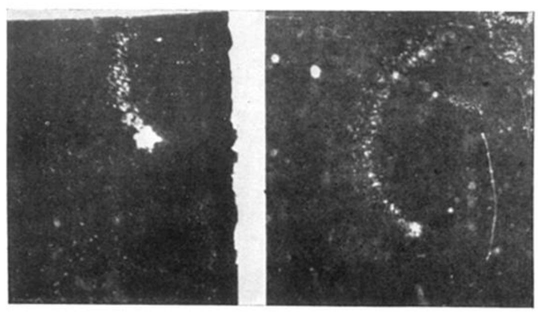

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