Further Experiments on the Recoil of the Nucleus in Beta-Decay

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Experiments on the recoil of the nucleus in the disintegration of Cl^{38} have been continued. The fact (which has been reported in earlier publications) that momentum is not conserved in the system consisting only of the nucleus and the emitted electron has been confirmed. By measuring the momenta of the electron and nucleus it has been possible to ascertain the direction of emission of the neutrino with respect to the direction of the electron in each case. Theoretical predictions according to both the Fermi and the K-U theory are plotted for comparison. The experimental data agree slightly better with the Fermi than with the K-U theory, but it is not safe to attach much significance to the results obtained on this aspect of the problem, because of the possibilities for rather large experimental errors. An investigation into the manner in which droplets in the cloud chamber are produced by the recoil atom has been carried out. Evidence is offered which indicates that the products resulting from dissociation of the gas molecules act as centers for condensation. This effect, in addition to ionization, accounts for the droplets observed.

INTRODUCTION

ABOUT a year ago[1,2] we reported our first results on the observation of the recoil of the atom resulting from the emission of a beta-particle by radiochlorine. In many of the cases observed the momentum of the atom was found to be much greater than the momentum of the emitted beta-particle, and this was considered as evidence that a third particle participates in the event; that is, evidence in the same sense that the apparent failure of the law of the conservation of energy is evidence for the participation of a third particle in the beta-disintegration. Since our last report we have repeated the experiment[3] with some improvements in technique and have obtained good confirmation of the important features of the results. It was our hope that with improved accuracy and a larger number of tracks we might be able to draw some conclusions about the direction of emission of the neutrino with respect to that of the electron. We have found that if the results indicate anything at all in this respect they favor slightly the predictions of the Fermi theory. The principal new fact which has appeared is that the production of droplets in the cloud chamber by the recoil atom is not due only to ionization, but is due in part to dissociation of molecules. The assumption that the atom makes a pair of droplets for each 30 ev energy is therefore not justified, and the calibration of the scale of energies has to be made in a different way, which will be described.

EXPERIMENTAL METHOD

The method used in the experiment may be reviewed briefly as follows. Radiochlorine, Cl^{38}, is produced by bombarding $MgCl_2$ with deuterons in the cyclotron, and is converted into ethyl chloride, C_2H_5Cl, which is a gas at ordinary temperatures. This is more satisfactory than ethylene dichloride, which we used in the earlier experiments, because of its greater volatility. Ten to 20 cc of ethyl chloride gas, made up partly of a nonradioactive and partly of the radioactive sample is introduced into the cloud chamber, which already contains air saturated with ethyl alcohol vapor at atmospheric pressure. The Cl^{38} atoms then disintegrate in the gas. The electric clearing field of the cloud chamber is short-circuited for a fraction of a second before each expansion, so as to allow the ions (and molecules) along the paths of the beta-rays to diffuse out into paths a few millimeters wide before the condensation occurs. It is by this means possible to count the individual droplets along the beta-ray path, and also to count the

[1] J. Halpern and H. R. Crane, Phys. Rev. **53**, 676(A) (1938).
[2] H. R. Crane and J. Halpern, Phys. Rev. **53**, 789 (1938).
[3] H. R. Crane and J. Halpern, Phys. Rev. **55**, 1123(A) (1939).

droplets in the spherical cluster at the point of origin of the track, which is presumably due to the recoil nucleus. The arrangement of the stereoscopic camera and the method of analyzing the photographs is the same as that described in our previous paper.

Results

The tracks obtained with the ethyl chloride vapor mixture are plotted in Fig. 1. Because the assumption that the energy of the recoil atom is 30 ev per droplet pair produced is no longer believed to be valid, we have been forced to adopt another method of normalizing the ordinate scale in terms of energy of the recoil atom. Fortunately we obtained one track of good quality in which the electron carried away nearly the entire energy of the disintegration. In this case we know the energy of the recoil atom, because the neutrino has nearly zero energy, and therefore its direction is unimportant. In other parts of the diagram (lower electron momentum) the highest of the points ought to correspond to cases in which the neutrino and electron were emitted in nearly the same direction, provided all directions are permitted, and provided there is a large number of points in the diagram. As a result of this reasoning, we have drawn the solid curves in Fig. 1 in the following way: We make the assumption that the energy of the neutrino is in all cases W_0-E_e where W_0 is the upper limit of energy of the beta-ray spectrum of Cl^{38} and E_e is the energy of the particular beta-ray. The momentum of the neutrino will then be $(W_0-E_e)/C$ on the assumption that it has zero rest mass. This will not be altered appreciably, however, by assuming a rest mass as large as that of the electron. We calculate the energy of the recoil atom as a function of the momentum of the beta-particle for the two limiting cases: (1) that the electron and neutrino are emitted in the same direction and (2) that they are emitted in opposite directions. These limits are shown as curves (1) and (2) in Fig. 1, the ordinate scale being adjusted to fit the point at 11 mc, in which case the momentum of the electron alone determines the energy of the recoil atom.

Evidence that momentum is not conserved in the two-particle system

Without going any further in the experiment, we can see in Fig. 1 strong indications that momentum is not conserved in the system consisting only of the emitted beta-particle and the nucleus. This is best shown by those cases in which the beta-particle had a small momentum and in which the recoil atom produced a large number of droplets. Fortunately it is not neces-

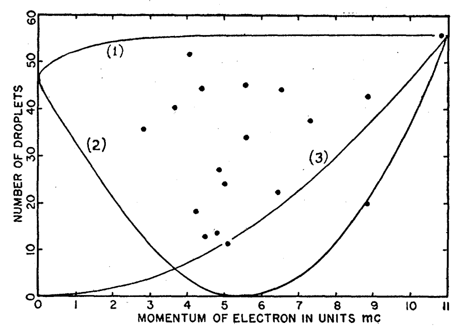

Fig. 1. Plot of the number of droplets in the cluster against the momentum of the emitted beta-particle. Each point in the diagram represents an individual disintegration, and the number of droplets in each cluster has been corrected for the number of droplets which is due to the escaping beta-particle, so that the number plotted represents only those due to the recoil atom. The curves shown have been calculated for the two limiting cases, (1) that in which the electron and neutrino escape in the same direction and (2) that in which they escape in opposite directions. Curve (3) shows what we should expect if momentum were conserved between the beta-particle and the nucleus (no neutrino).

sary here to know the absolute relation between the number of droplets and the energy of the recoil atom. The mere fact that as large a cluster is often associated with a beta-particle of 3 or 4 mc momentum as with a beta-particle of nine or ten mc momentum indicates that conservation of momentum in the two-particle system is not possible, and the simplest assumption to make is that a third particle participates in the event

Direction of emission of the neutrino

On the assumption that a neutrino participates in the disintegration, and that the above formulae for its energy and momentum are correct, we should be able to calculate the angle, ϕ, between the directions of emission of the neutrino and the electron for any one of the points in the diagram, Fig. 1. This would also have to be based upon some assumption as to the relation between the number of droplets and the energy of the recoil atom. We have calculated the angle ϕ for all the cases in the diagram, on the simple assumption that the energy of the recoil atom is proportional to the number of droplets produced. We are aware that the relation is more complicated than this, but since it is not possible to determine it, the assumption that was made will have to suffice for a first approximation. Fig. 2 shows the distribution of the cases with respect to ϕ. On the same diagram theoretical curves for the distribution according to the K-U and Fermi theories are shown. Formulae for these have been given by Bloch and Moller[4] and by Hebb.[5] According to Bloch and Moller's formula, which is given in a convenient form for our purpose, the probability that the neutrino will be emitted within the solid angle $d\Omega$ at an angle ϕ with respect to the direction of the electron is

$$\text{K-U:} \quad \frac{1}{4\pi}\left(1-\frac{v}{c}\cos\phi\right)d\Omega$$

$$\text{Fermi:} \quad \frac{1}{4\pi}\left(1+\frac{v}{c}\cos\phi\right)d\Omega$$

for a given velocity, v, of the electron. In plotting these we have transformed them into terms of the probability of emission within the angular interval $d\phi$ at an angle ϕ, in order to place the curves in the same diagram as our experimental

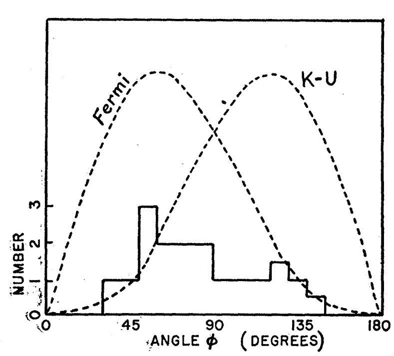

FIG. 2. Distribution of the angle between the directions of emission of the neutrino and the electron. The theoretical predictions based upon the K-U and the Fermi theories are given for comparison.

values. The formulae become

$$\text{K-U:} \quad \tfrac{1}{2}\sin\phi\left(1-\frac{v}{c}\cos\phi\right)d\phi$$

$$\text{Fermi:} \quad \tfrac{1}{2}\sin\phi\left(1+\frac{v}{c}\cos\phi\right)d\phi.$$

In the experimental data with which we are concerned, v/c ranges from 0.94 to 0.995. Rather than subdivide the data according to v/c, we have taken an arbitrary value, 0.98, to serve for all the data. The choice of this value is of little importance in determining the important features of the curves. It is seen in Fig. 2 that the experimental distribution is in slightly better agreement with the Fermi than with the K-U theory. Very little weight can be placed in this evidence, however, in view of the many possibilities for systematic error, and in view of the small number of points in the diagram. It is unsafe to draw any conclusions from this part of the experiment.

The Roll of Molecular Dissociation in the Production of Droplets

In the course of our recent experiments two facts become apparent: (1) The number of droplets in a cluster was often more than could be accounted for by ionization by the recoil atom[6, 7] and (2) the number of droplets in the clusters (ordinate scale in Fig. 1) was influenced by the composition of the gas present in the chamber. We now believe that we have good evidence showing that droplets are caused by certain neutral molecules which are formed as a result of the dissociation of O_2, N_2, etc. by the recoil atom, and that this effect accounts for the two facts mentioned above. The existence of this effect is fortunate, because it increases the sensitivity of the experimental method.

It is well known that a heavy, slowly moving particle can be very efficient in bringing about dissociation of the molecules of a gas through which it passes. The amount of dissociation will be large compared to the amount of ionization when (to say it in simple language) the time of interaction with the gas molecule is short com-

[4] F. Bloch and C. Moller, Nature **136**, 911 (1935).
[5] M. H. Hebb, Physica **5**, 701 (1938).
[6] L. Wertenstein, Phys. Rev. **54**, 306 (1938).
[7] H. R. Crane and J. Halpern, Phys. Rev. **54**, 306 (1938).

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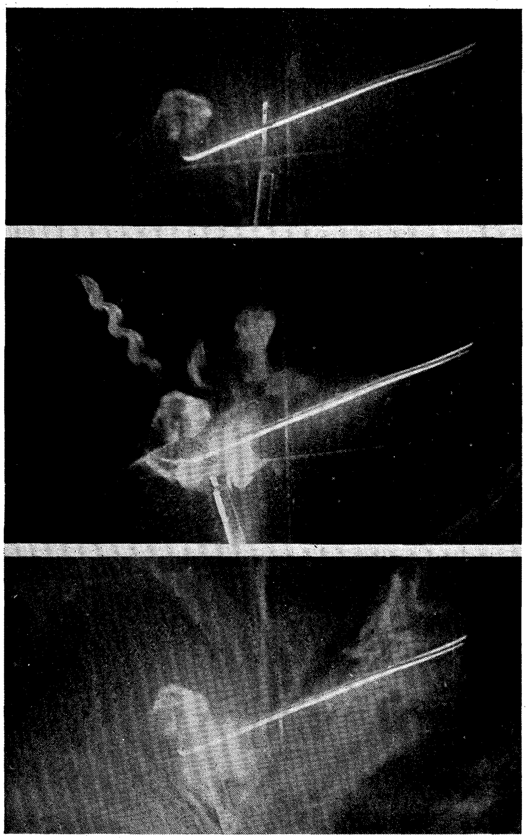

FIG. 3. Series of three consecutive photographs showing the effect of introducing a minute quantity of NO_2 into the cloud chamber. (1) (Top photograph.) The small capillary containing NO_2 turned into position ready to be broken by the cutter which is attached to the piston of the chamber. (2) Gas issuing from the broken capillary at the time of the first expansion of the chamber. The sinusoidal form of the main gas stream is due to vibration of the wire which holds the capillary. (3) The next expansion, showing that the cloud is spreading to the entire chamber.

pared to the periods of oscillation of the nuclei in the molecule and long compared to the classical periods of rotation of the electrons in the atomic orbits. The perturbation of the electrons will then be predominately adiabatic, while molecular excitation will occur, frequently to the dissociation level. In air, practically all of the atoms O and N thus set free will combine with other molecules to form NO_2, N_2O, O_3 etc. The combination will have to occur in triple collisions, to satisfy momentum and energy conservation, but at atmospheric pressure triple collisions are so frequent that the chemical reaction will be completed in a time which is short compared to

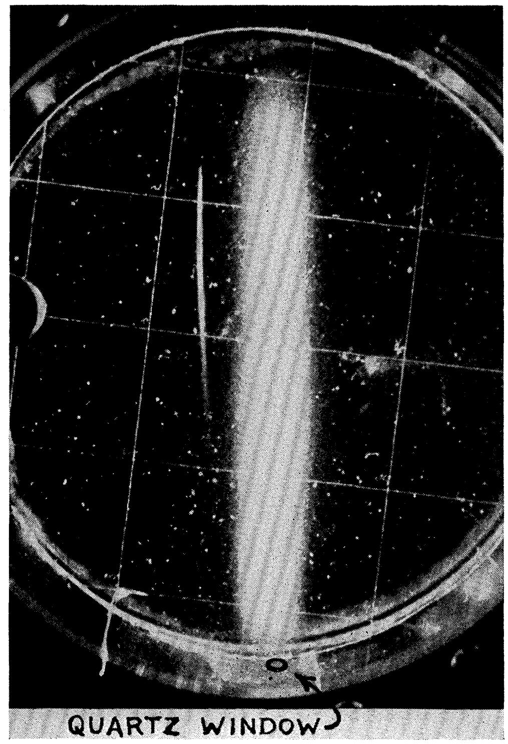

FIG. 4. Photograph of cloud chamber expansion which was made a few seconds after a narrow pencil of ultraviolet light was projected across the chamber. Before the expansion all the ions were drawn out of the space, so the effect shown here is due to neutral molecules. The small streak which appears at the side is an alpha-particle track.

the sensitive time of the cloud chamber. In our experiment there is also alcohol vapor, (C_2H_5OH) and ethyl chloride (C_2H_5Cl) in the cloud chamber, which increase the number of possible reactions. It is our belief that some, at least, of the molecules formed as a result of the dissociation, act as centers for the condensation of droplets in the cloud chamber.

TABLE I. *Resumé of results obtained upon the introduction into the cloud chamber of minute quantities of various gases.*

Substance Introduced	Estimated Concentration in Chamber	Result
NO_2	10^{-8}	dense cloud
N_2O	10^{-7}	medium cloud
CO_2	10^{-7}	no cloud
H_2O		no cloud
air		no cloud
HNO_3	10^{-10}	very dense cloud
NH_3	10^{-8}	very little cloud

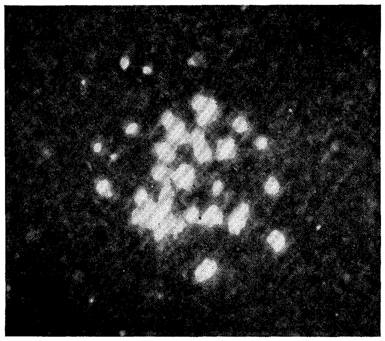

FIG. 5. Spherical cluster of droplets due to the recoil atom. In this case the ions have been drawn away, and the droplets which appear must therefore have condensed upon neutral molecules.

Experiments with NO_2, CO_2, N_2O, HNO_3, H_2O and air

The following experiments were tried to test the possibility mentioned above. A piece of drawn-out glass tubing about 1/10 mm inside diameter was filled with NO_2 gas at atmospheric pressure and a piece about 1 cm long was sealed off. This was placed in a clamp in the center of the cloud chamber. After the chamber had cleared and had become sensitive to electron tracks, the end of the capillary was clipped off just at the time of an expansion, by means of a cutter which was moved by the piston of the chamber. The stream of gas issuing from the capillary produced a dense cloud, and on the next expansion the cloud filled the entire chamber. A typical series of three photographs is shown in Fig. 3.

The release of like quantities of CO_2, H_2O vapor, and air, caused no appreciable cloud. N_2O caused a cloud, but not such a dense one as that caused by NO_2. The most potent agent for producing condensation which we found was nitric acid vapor. For testing this we cut a small round hole in the glass top-plate of the chamber and closed it with a rubber cork. The chamber was then cleared and adjusted so that good electron tracks were obtained. A fine glass filament (less than 0.1 mm diameter) was then wet with nitric acid. The cork was removed, and the filament quickly lowered into the chamber and out again without touching any part, and the cork replaced. Upon the next expansion an exceedingly dense cloud appeared, which soon filled the entire chamber. This was due to the nitric acid, and not to anything else which might have entered the chamber when the cork was removed, because the same motions were carried out without dipping the glass in the acid, and no cloud was produced. In each case in which a cloud was produced, it was not found possible to clear the chamber by repeated expansions (up to about 20 were tried). The chamber was opened, dried thoroughly with a stream of air and put together with fresh alcohol after each experiment.

A resumé of the substances tried, and the results are given in Table I. The question arose as to whether the cloud was caused by a fairly high concentration of the substance in a local region near the point where it was introduced. We therefore repeated the experiments, allowing time for the substance to diffuse throughout the chamber before bringing about the expansion. The results were the same.

Experiments with ultraviolet light

The question of concentration of the substance introduced in the air in the chamber has to be considered rather carefully. We must be sure that a droplet can grow around a *single molecule* of the substance. If the concentration were high, the condensation of a droplet might be initiated by the accidental grouping together of several molecules of the substance. If this were so, the result would have no bearing upon the case in which the substance is produced by the recoil atom in the beta-disintegration, because there the concentration is so small that two molecules of the substance would almost never come together in the same incipient droplet.

In order to liberate an extremely small amount of atomic oxygen in the chamber we resorted to the use of ultraviolet light. A quartz window 2 mm in diameter was cemented to the side wall of the chamber. A few seconds before the expansion a small arc was made just outside the window by touching a pair of copper wires together. The arc carried about two amperes for about a quarter of a second. The result was very striking, and is shown in Fig. 4. Photographs were taken with various intervals of time, from one to ten seconds, between the spark and the expansion, and at all times the electrical clearing field was left on the chamber, so we are sure that none of the effects observed are due to ions. The only effect of varying the time interval was a variation in the width of the clouded strip in the chamber, due to diffusion. The extremely small amounts of the compounds synthesized by the weak ultraviolet light make it seem reasonably certain that the effect observed is not an effect of the concentration of the substances, but is due to the action of individual molecules in initiating the formation of droplets.

Isolation of droplet clusters produced by uncharged molecules

With this encouragement we proceeded to a more direct test. We repeated the experiment on the recoil of the atom resulting from the decay of Cl^{38}, with all conditions the same as before except that the electrical clearing field was not removed from the chamber at the time of expansion. The expectation was that if a Cl^{38} atom should disintegrate a short time (fraction of a second) before the expansion, the *ions* would be drawn out of the chamber by the electric field, while *uncharged* molecules would remain, and would move about only by diffusion. Many isolated clusters like the one shown in Fig. 5 were observed. In this case the ions comprising the electron track have been drawn away. The ions produced by the recoil atom have also been drawn away, and what remains is presumably due to neutral molecules, which have had time enough to diffuse into a cluster a few millimeters in diameter. A plot of the number of

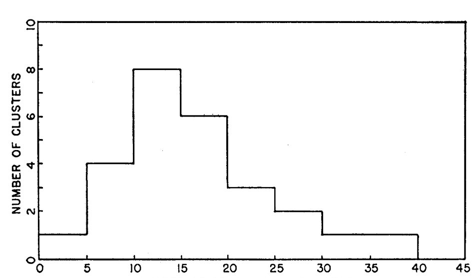

FIG. 6. Plot of the number of droplets in the clusters which were due to neutral molecules.

droplets in the clusters of this type which we obtained is shown in Fig. 6. The shape of this is complicated by the existence of the lower energy component[2] in the chlorine beta-ray spectrum. The clusters due to the lower component cannot be sorted out as they could in the other data, because of the absence of the electron track. The plot does show, however, that in some cases as many as 40 droplets are due to neutral molecules, whereas the total number of droplets (due to ions and molecules) extends up to only about 60. This indicates the great importance of the effects of dissociation.

Concluding Remarks

A few remarks about the possibilities for extension of this experiment may be set down at this point. Since the number of droplets produced for a given energy of the recoil atom is dependent upon the chemical composition of the gas in the cloud chamber, it might be possible to find a gas mixture which would give many more droplets than we obtained in this experiment. Besides increasing the accuracy of the measurements on Cl^{38}, this might allow us to work with other radioactive elements, in which the energy of recoil is smaller.

The principal unknown in the method is, and always has been, the relation between the number of droplets and the energy of the recoil atom. Because of the complexity of the chemical reactions which can give rise to droplets, it is difficult to think of an auxiliary experiment in which this relation could be measured.

It may be pointed out that the fact that individual molecules of certain polar compounds can make their presence known in a cloud chamber, may have interesting applications in other kinds of research, such as physical chemistry.

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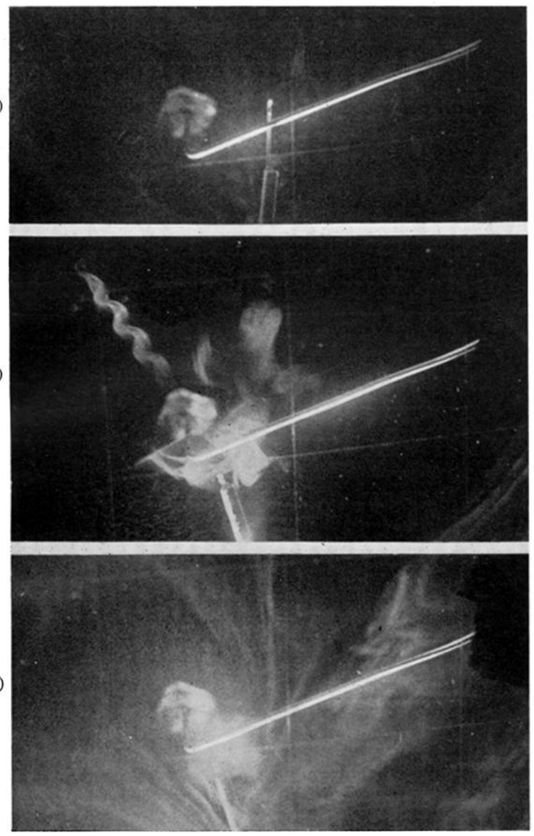

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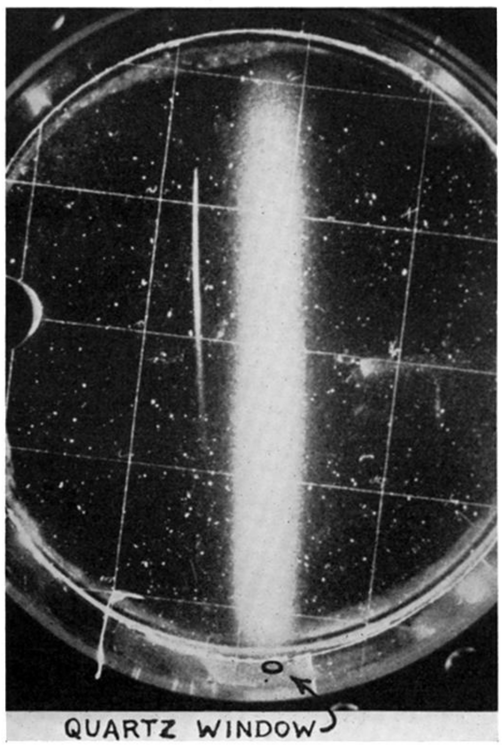

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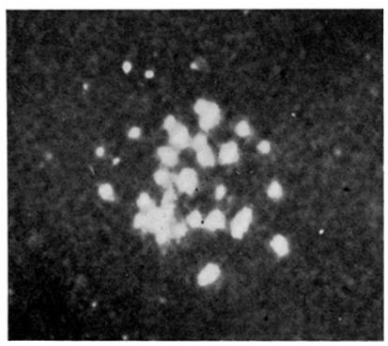

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