Cloud Chamber Search for Particles Ionizing Less Than an Electron*

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Since ionization due to a charged particle varies with the square of its charge, a very clean cloud chamber can be used to search for particles having charges, *ze*, much less than the electronic charge. Similar remarks hold true for magnetic monopoles of relativistic speed. A horizontal cloud chamber constructed by J. A. Bearden was employed, in the gamma flux from a radium source, to search for such particles. The sensitive time was about 1.5 seconds. The background was at least 60 times less than values commonly reported for "clean" chambers. No subionizers with z in the range $\frac{1}{6}$ to $\frac{1}{2}$ were seen during a time in which about 900 electron tracks were recorded, one million gamma rays traversed the chamber, and 3 million disintegrations were available to give rise to such particles.

A vertical chamber 12 in. high was used to look for subionizers in the cosmic ray flux. The background ranged from 0.05 to 1.0 drop per cc, with a usable sensitive time of 0.3 second. Technique for a more limited search was developed; use was made of the fact that background drops are single and well separated, while there are many clumps of ions along a track. No subionizers appeared in a body of photographs containing 550 electron and μ-meson tracks.

It was shown by study of "ghost tracks" that neutral nuclei are a major source of the background commonly encountered in tall chambers.

1. INTRODUCTION

THIS work arose from realization that while the discovery of mesons has been going on, there has been, to the best of our knowledge, no serious search for particles of relativistic speed which ionize more lightly than the electron. Such particles might be either subelectrons or magnetic monopoles.

Roughly, the primary ionization due to a bombarder of charge ze is equal to z^2 times the ionization due to an electron of equal speed. Also, the ionization by a pole of strength g (in emu) is $(g/e)^2(v/c)^2$ times the value for an electron of the same speed v. To a good approximation, the mass of the bombarder does not affect the ionization.

It is well known that Ehrenhaft claimed the discovery of stable subelectrons and monopoles, attached to microscopic particles floating in a gas. The claim in regard to subelectrons was refuted by Millikan, and in the early 1940's several investigators found themselves unable to obtain the results of Ehrenhaft[1] on monopoles. The question arises, are there other classes of experiments in which such particles might have been detected, if looked for? It is probably fair to say that if stable charges greater or less than e were present in ordinary matter in a concentration of the order 10^{-5}, they would not have been detected in any spectroscopic or mass-spectroscopic investigations done up to the present; indications of such particles would have been treated as due to impurities, noise, or experimental defects. A similar remark applies to stable poles.

This paper is not concerned with such entities at rest. For several reasons, it seemed more reasonable to look for them in a state of rapid motion. Firstly, if the particles have large energy, one can look for their tracks in cloud chambers or emulsions. Secondly, if they are unstable, one should seek them in the cosmic-ray flux, or in the presence of radioactive sources. It is clear that only pictorial detectors should be used, and that low background is essential.

If a wide range of values of e and of m is considered, the field of search becomes too broad for study by a small group. Particles with a charge greater than e, at given speed, ionize more heavily than an electron of the same speed. In principle, it is possible to differentiate between a new type of particle, with speed close to c and a charge greater than e, and slow electrons, or μ mesons, but in practice there would often be confusion. Hence we decided to look only for particles with a specific ionization well below the value pertaining to relativistic electrons. Such particles will be called subionizers, regardless of whether they are charges or monopoles.

This decision precluded the use of emulsion as a detector, leaving the diffusion chamber, the bubble chamber, and the Wilson chamber for consideration. Each of these instruments would have advantages in different portions of a comprehensive search. However, we were not satisfied that the background in a diffusion chamber or a bubble chamber could be reduced to very low values, and it seemed that it would be valuable to be able to record individual ions. Therefore, the work has been done with Wilson chambers. The sensitive times were made as long as was possible without running into accessory difficulties. At first, we intended to apply a magnetic field, but there are reasons (Sec. 2) for

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[1] See, for example, F. Ehrenhaft, J. Franklin Inst. **233**, 235 (1942); V. D. Hopper, Phys. Rev. **66**, 93 (1944).

working with undeflected tracks, so a field was not employed.

It should be stated at once that with two chambers having very different characteristics no authentic example of a subionizer has come to light.

2. EXPECTED PROPERTIES OF SUBELECTRONS

Consider a hypothetical particle of charge ze, rest mass m and relativistic speed, $v=Bc$. Let z be a fraction not too close to unity, and let m_e be the rest mass of the target electrons. In an initial search for the type ze, it is convenient to focus attention on the primary specific ionization, which is nearly proportional to z^2 when B is held fixed. The formula[2] for the number of primary ion pairs per cm is

$$I_p=\left(\frac{2Cm_ec^2rz^2}{V_0}\right)\frac{1}{B^2}\left[\ln\left(\frac{2m_ec^2B^2}{(1-B^2)V_0}\right)+s-B^2\right]. \quad (1)$$

Here C stands for ZnS, where n is the number of atoms of atomic number Z per cc, S is the classical area of an electron, 0.26 barn; and r and s are dimensionless numbers which depend on the structure of the atom. The theoretical values of r and s for the case of hydrogen atoms are $r=0.285$ and $s=3.04$. V_0 is the mean ionization energy of the outer shell of the atom. Actually, s depends on z, Z, and B; but it is relatively small compared with the logarithmic term in the cases we shall consider. Furthermore, it is believed that the dependence of s on Z is slight.

Figure 1 helps us to appreciate the dependence of the primary ionization on z and on the mass of the particle. The ordinate is I_p divided by the first parenthesis on the right of Eq. (1). Curve A refers to electrons. It happens that the minimum primary ionization of an electron in air is about 20 ion pairs per cm, so the dimensionless ordinates agree closely with the actual specific ionization in that substance. By shifting the electron curve bodily two decades to the left, we obtain curve B, applying to a particle with the electron charge but a mass of $m_e/100$. Curves C and D refer to particles with charges smaller by a factor of about three.

If the hypothetical particle is produced in a radioactive process we would expect its energy to be in the general neighborhood of 1 Mev. If it arises from the cosmic rays, the energy should be of the order 10^9 ev. In either case, we see from the curves that a particle with charge $e/3$ could readily be distinguished from an electron or meson over a very wide range of energies, including the values mentioned above. Furthermore, this is true for a wide range of masses.

This means that in a first search for subionizers one can afford to dispense with attempts to obtain the mass and velocity. If we used a magnetic field, we would

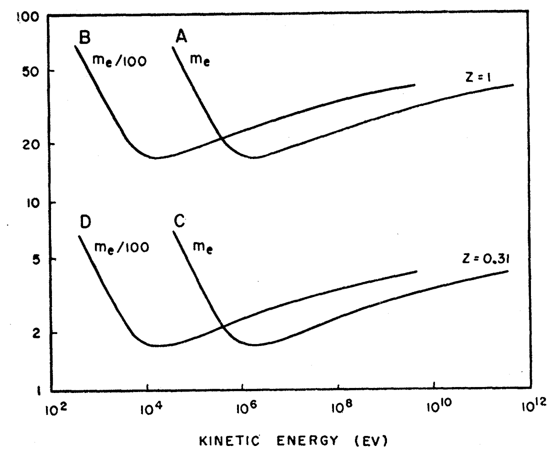

FIG. 1. Dependence of primary ionization on kinetic energy. The ordinates are a dimensionless measure of the primary ionization by particles whose mass and charge are shown.

have to examine configurations of droplets to see whether they lie on spirals, with axes parallel to the field. Even without attempts to use further criteria for determining the mass and the speed, the labor required would become prohibitive. It is fortunate that the problem can be reduced to a search for straight tracks with low specific ionization. Operating in this way, we can search for particles with charges lying in a range of values, *provided* that the mass and velocity lie in certain wide ranges.

The reason for this proviso is as follows. For particles of given energy, if the mass is chosen sufficiently small, there will be important angular deflections due to bremsstrahlung and multiple scattering. On the other hand, if the mass is chosen sufficiently great the particle will no longer be relativistic; in both cases the experimental method just outlined would have to be modified. We shall restrict discussion to cases in which these difficulties do not arise.

Finally, we wish to call attention to a curious possibility, by citing an example. If there were a particle bearing the electronic charge but having a rest mass of say 5000 ev, then such a particle, endowed with an energy of 10 000 ev or more, would initially lose energy at the same rate as a relativistic electron; namely, about 2000 ev per cm in air. However, the track would terminate in a short dense tail, the whole affair being only a few cm long. We have not seen anything of this kind in our studies.

3. EXPECTED PROPERTIES OF MONOPOLES

Dirac Poles

Dirac[3] published calculations which led him to the view that if magnetic monopoles exist they have pole strengths given, in emu, by the value

$$g_n=n(137/2)e=3.28\times10^{-8}n. \quad (2)$$

[2] H. A. Bethe, *Handbuch der Physik* (Verlag Julius Springer, Berlin, 1933), Vol. 24.1, p. 518; and B. Rossi, *High-Energy Particles* (Prentice-Hall, Inc., New York, 1952), p. 45.

[3] P. A. M. Dirac, Proc. Roy. Soc. (London) **A133**, 60 (1931); Phys. Rev. **74**, 817 (1948).

Here n is an integer and e is expressed in esu. Dirac's theory contains nothing to determine either the mass of the poles or the value of n. Later writers have often assumed that $n=1$, to simplify discussions on orders of magnitude. We shall do the same.

Dirac wrote a wave equation for an electron moving in the field of a stationary pole. This equation and related matters have been studied by Tamm,[4] and later by several others. The vector potential of the pole is discontinuous along a half-line extending out from the pole. This feature deserves a word of interpretation. In effect, Dirac has employed the vector potential of a straight half-infinite solenoid which terminates at the position of the pole. The cross section of the solenoid can be made to approach zero, with parallel increase of the current in such a way that the open end of the solenoid simulates the pole. It is natural to expect curious behavior of the electron in the neighborhood of this idealized solenoid. The classical orbits of the electron are spirals on a conical surface.

Previous Experiments

Tuve[5] considered experiments for detecting Dirac poles, based on several interesting points. A Dirac pole would gain an energy of 4×10^8 ev in falling freely through a 200-gauss solenoid only 1 meter long. Such a pole falling to the magnetic pole of the earth from a distance of several earth radii would acquire about 4×10^{12} ev. Ross Gunn noticed the same point independently.

McNish pointed out to Tuve the possibility of multiple acceleration in a re-entrant solenoid, since the poles could be guided by electric fields. Dr. Tuve has kindly informed us that a search was made with a cloud chamber in a magnetic field; and that since the findings were indefinite in character he did not publish them.

So far as we can find, the only other experiments on rapidly moving poles, before our own, are those done by Malkus[6] at Teller's suggestion. His work was a search for Dirac poles created by the primary cosmic radiation. It is assumed that the poles are sufficiently long-lived to facilitate detection. If they were created in pairs, each member of a pair would have to wait a long time to find a mate capable of annihilating it. These poles would come to low terminal velocity in the earth's magnetic field after traversing a relatively short path in the atmosphere. Malkus' experiment depends on accelerating them in a vacuum, in a field much stronger than that of the earth.[7] He set up a solenoid 100 cm long and 20 cm in diameter, oriented parallel to the earth's field, on the laboratory roof. It surrounded an evacuated tube capped with thin mica windows. At the bottom there was a nuclear emulsion. When the solenoid was energized to 250 gauss, it was threaded by lines of force which originally covered an area of about 8300 cm^2. This large collection area is a great advantage. Dirac poles passing through the tube should gain 500 Mev, and should lose only 50 Mev in passing through a window above the emulsion. Tracks several hundred microns long would be expected. The experiment ran for two weeks. There were no heavy tracks other than a few caused by alpha particles. According to Malkus, this result means that the rate of arrival of Dirac poles, based on the large collection area, was less than 10^{-10} poles per cm^2 per sec, and the cross section for production by cosmic ray primaries was less than 3×10^{-35} cm^2.

Interaction of Poles With Matter and Radiation

We now consider how the production, scattering, and energy loss of poles depend on pole strength g and mass m_g. To explain the scattering of poles qualitatively, we note that a pole in motion with speed v would produce circular lines of electric force, related to the velocity vector in the sense of a left-handed screw. The electric intensity would be

$$E=g\frac{v}{c}\frac{\sin\varphi}{r^2}, \tag{3}$$

where φ is the angle between v and r. Thus we might expect that the cross section of a charge Ze for scattering poles through an angle θ could be obtained, in order of magnitude, by putting gv/c in place of the charge ze of the bombarder, in the Rutherford cross section. In the center-of-mass system, we would have

$$\left(\frac{Zeg(v/c)}{2\mu v^2}\right)^2\frac{1}{\sin^4(\theta/2)} \tag{4}$$

for the scattering cross section of a pole striking a nucleus. Here we have used the reduced mass μ, because the mass of the pole may be great enough to make it necessary.

Some of the properties of Dirac poles have been calculated by Cole, and independently by Bauer.[8] Cole's calculations were on a classical basis, while Bauer obtained both classical and wave-mechanical results, for the sake of comparison. Where the results of these investigators overlap, they agree, looking aside from factors of the order unity which arise from approximations. Furthermore the classical and wave-mechani-

[4] I. Tamm, Z. Physik **71**, 141 (1931).
[5] M. A. Tuve, Phys. Rev. **43**, 770 (1933); Terrestrial Magnetism and Atmospheric Elec. **38**, 260 (1933).
[6] W. V. R. Malkus, Phys. Rev. **83**, 899 (1951).
[7] It is interesting to note that easily available magnetic fields can feed energy to certain types of magnetic poles at a sufficient rate to overcome their ionization loss in air at NTP. For poles at relativistic energy the field which balances this loss is

$$H=5.1p(g/e)\log_{10}[T_0/J(1-B^2)].$$

Here p is the pressure of the air in atmospheres; T_0 is $\frac{1}{2}m_gv^2$, where m_g is the pole-mass; J is the average ionization energy of the gas. For example, a field of about 3000 gauss can increase the speed of a Dirac pole having an energy of 1 Bev, at NTP. We call this effect the runaway phenomenon.
[8] H. J. D. Cole, Proc. Cambridge Phil. Soc. **47**, 196 (1951); E. Bauer, Proc. Cambridge Phil. Soc. **47**, 777 (1951).

cal results agree, aside from such minor differences. In particular Bauer obtains the formula (4) for the scattering cross section. Cole and Bauer give some numerical results for the case of Dirac poles, endowed with masses of the order of $(137/2)^2 m_e$, or about 2.55 proton masses. As far as we know, Dirac never committed himself on the mass of his poles, which does not come out of his theory. The value mentioned here is a guess, based on setting the classical radius of the pole, $g^2/m_g c^2$, equal to the electron radius. Bauer remarked that if the Dirac pole had electronic mass it would radiate so strongly that prior detection would have been very likely. We consider this statement about detection to be doubtful. Using the formulas of Cole and Bauer, we can compare the values of various cross sections, for poles of any charge and mass, with the corresponding values for electrons. Since a comprehensive list of such ratios is valuable in understanding how various types of poles would behave, we supply it in Table I. The subscripts g, e, and n refer to poles, electrons, and nuclei, respectively. Some quantities not really needed for discussion of our experiments are included for completeness.

For simplicity the table refers only to the relativistic case, and no attention is paid to slowly varying logarithmic terms in the cross sections.

We see from items 1 and 2 that our experiments designed to detect subionizing charges, ze, serve at the same time as a search for poles. The range of pole strengths which can be covered is the same as that of ze.

The cross section for production of a pair of subionizing charges of mass m is approximately

$$S(z,m) = z^4 (m/m_e)^2 S_e, \tag{5}$$

where S_e is the electron pair cross section. Thus there is a considerable range of values of z and m which lead to easily measurable cross sections for production of subionizing pairs. Furthermore, the cross section for pole-pair production by photons can be as large as that for electron pairs, in a variety of cases. There are two cases of special interest in which these cross sections are equal. In the first, the pole is an electron-mate, that is, $g=e$ and $m_g=m_e$; in the second, the pole is a Dirac-type endowed with a mass of $(137/2)^2 m_e$. Of course, the thresholds for production of the two kinds are entirely different. The electron-mate type could be produced copiously by gamma rays, and in magnet cloud chambers such pole pairs would show up as tracks deflected parabolically in the direction of the field. We have not made a search for such particles. Dr. Carl Anderson has told us that he examined one curious event from this point of view, without favorable result. It would seem that further search for such events would be worth while, though it is probable that if the large cross section predicted were realized in nature these poles would have already been detected.

The situation in regard to the heavy Dirac poles is quite different. Their ranges are small—a few cm for a kinetic energy of 1 Bev. According to Bauer, the specific energy loss does not rise near the end of the track. This occurs because the combination gv/c replaces ze in the single scattering cross section. Thus a pair of these poles in a chamber at NTP would have an appearance distinguishing it clearly from a two-prong star. If we trust the pair-production cross section in air (about 0.1 barn), it appears likely that heavy stable Dirac poles would have been detected in the Malkus experiment. A definitive statement would require detailed studies of the atmospheric flux of photons having energies superior to 5 Bev.

TABLE I. Comparison of pole properties with those of an electron, assuming that both are relativistic.

Quantity	(Value for pole / value for electron)
Energy loss per cm	$(g/e)^2$
Ion pairs per cm	$(g/e)^2$
Cross section, single nuclear scattering	$(g/e)^2(\mu_{e,n}/\mu_{g,n})^2$
Bremsstrahlung cross section	$(g/e)^2(\mu_{e,n}/\mu_{g,n})^2$
Average angle of multiple scattering after traversing one cm	$(g/e)(\mu_{e,n}/\mu_{g,n})$
Cross section for pole-pair production by photons in the nuclear field	$(g/e)^4(m_e/m_g)^2$
Two-pole annihilation	$(g/e)^4(m_e/m_g)^2$

In exploratory work like ours, one should not commit himself to specific theories, except as a guide to the possibilities. While the speculations of Dirac are attractive, they are based on an assumption introduced at line 7 of page 63 of his first paper, which can be questioned. Therefore we shall not hesitate to consider poles which do not have the magnitude preferred by Dirac.

Many previous writers have discussed the symmetrical generalization of Maxwell's equations which results from introducing poles in addition to charges. We have taken the trouble to verify that this set of symmetrical equations is Lorentz-invariant. We have little doubt that if poles are found in nature they will obey this set of equations, but the question now before us is, do they exist?

4. METHODS OF SEARCH FOR SUBIONIZERS WITH WILSON CHAMBERS OF LONG SENSITIVE TIME

In looking for subionizers in the Wilson chamber one desires very low background, since the lower limit of z which can be covered in the search will depend on the extent to which tracks can be simulated by chance configurations of droplets, lying nearly in a straight line. In air at NTP the specific primary ionization of a relativistic electron is about 21 ion pairs per cm, so if z were 0.1 we would have a track with a spacing of 5 cm between primary events. In cloud chambers with the usual background density it would be nearly impossible to seek for subionizers with so low a z value.

Also, one desires a long sensitive time, since the particles may be very rare. A long sensitive time provides two other advantages. One can take several pictures per expansion so that ordinarily, in at least one picture of each sequence, all droplets formed can grow to full size. This prevents the mistake of supposing that an insufficiently developed electron track is the track of a subionizer. (See, however, Sec. 5.) The use of multiple pictures makes it possible to neglect background droplets which are present before a track is formed, or which come in after it has grown to full density.

It is a great advantage to use enough resolution for photography of individual droplets, because it helps in distinguishing tracks from random background. Typically, background droplets form on neutrals, and therefore are single, while isolated ion pairs along tracks may register as doublets if the track is formed before full supersaturation is reached. The detection of such droplet pairs can be helped somewhat by retention of a weak sweep field. Of course, this is not true for tracks formed after the supersaturation necessary for good drop-formation on charges of both signs has been attained. Consider, now, how the track of a subionizer should look. A newly formed electron track in air at NTP has many clumps which may overlap. On the other hand, in the track of a subionizer with z of the order 0.5 or less, the overlapping between the products of adjacent primary events would be much reduced. Thus, if we do not try to push the search down to unduly low values of z, it is easy to tell the difference between a genuine track and a mere accident of background formation.

To summarize, our basic requirements were a chamber of long sensitive time with low background, and arrangements for taking several pictures per expansion, with resolution of individual droplets.

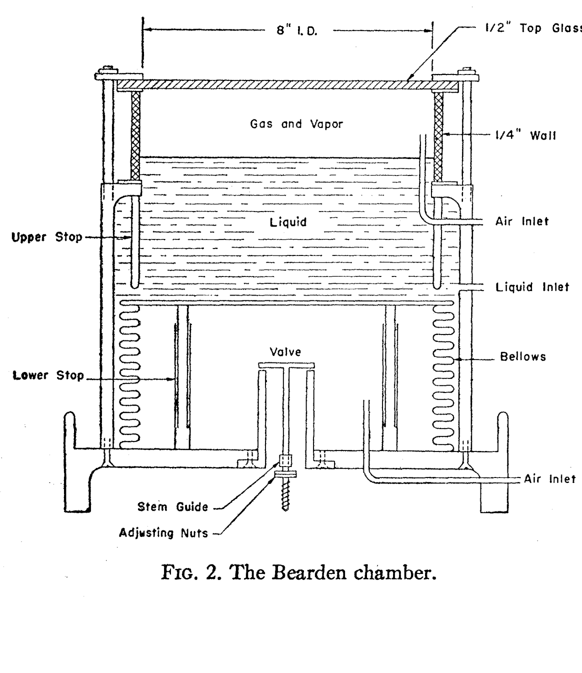

FIG. 2. The Bearden chamber.

The investigation fell into two related parts, because we desired to search for subionizers in the flux from a radioactive source and also in the cosmic ray flux. The work with a radioactive source was done with a horizontal chamber kindly loaned to us by Bearden.[9] From his investigation it was known to have a sensitive time as high as two seconds, and to be very clean. There was an agreeable surprise as to the cleanliness attainable. Eventually, it became possible to control this chamber so that there was not a single background droplet in about 15% of the expansions, and only a few isolated droplets in another 40%. The presence of higher background in the remainder is of instrumental origin, explained in Sec. 5.

Since the active volume was about 600 cc, this means that in the best 15% of the expansions we had a background more than sixty times lower than that in chambers described as clean in the literature. For example, Wilson[10] indicates that a chamber with a background of one drop in 10 cc would be considered very clean.

A second chamber, 12 in.$\times$24 in.$\times$6 in., was constructed to search for subionizers in the cosmic rays. This chamber showed background of the level commonly achieved with cosmic-ray chambers of about the same size. Led on by the low background achieved in the Bearden chamber, we made many attempts to reduce the background in the large one. The result was that we found a main cause of the background. The chamber was operated with the 12-in. dimension vertical and had a useful sensitive time of about 0.3 second. Under these conditions, only the portions of tracks in the close vicinity of the bottom can fall out before the droplets evaporate. Previous workers have noted that numerous nuclei are left behind by evaporation of the droplets. Under stable thermal conditions, diffuse ghosts of tracks from the previous expansion may appear; and neutrals produced in the interval between expansions may also yield broad tracks. Whatever their origin may be, we find that these remnants of tracks are very numerous. There is every reason to believe that they are ample to explain the level of background in large vertical chambers. While intermediate expansions can alleviate this situation, they cannot cure it. (Sec. 6.) We are not implying that this is the sole cause of background in this chamber, but it is a major cause. The background ran from 0.05 to about 1 drop per cc. Nevertheless, with stereoscopic viewing, a search for subionizers could be carried out. This is made possible by the fact already mentioned, that genuine tracks have many clumps of ionization.

[9] J. A. Bearden, Rev. Sci. Instr. 6, 256 (1935).

[10] J. G. Wilson, *Cloud Chamber Technique* (Cambridge University Press, Cambridge, England, 1951), pp. 53–4. In this connection the long sensitive time of our chamber should be considered.

5. SEARCH FOR SUBIONIZERS FROM A RADIUM SOURCE

In these experiments[11] we used a sealed radium source of 4 millicuries, located in a lead shield at a distance of 40 in. from the chamber. The gamma rays were collimated by a gap between lead blocks so that most of those hitting the chamber lay close to a plane through the center of the active volume. No filter was used. All beta rays were stopped by the chamber wall. On the average there were 14 tracks from the source and 3 cosmic rays, per expansion.

The Chamber and Its Properties

The Bearden chamber is shown in cross section in Fig. 2. The piston is a large body of water-alcohol mixture, made opaque with black dye. It is compressed by a Sylphon which moves between fixed stops. The final expansion ratio can be adjusted by introduction or withdrawal of liquid. We have found it convenient to use a sensitive time of about 1.5 seconds, provided by slow expansion.

A coarse adjustment of speed can be made by changing the pressure in the chamber, while fine adjustment is secured by varying the rate of flow of the driving air and the rate of escape through valve V. These two adjustments are not independent. Figure 3 shows roughly what happens. If the expansion were instantaneous, condensation on ions alone would be possible in a narrow range of values of the volume expansion ratio. As time goes on, heat liberated from the walls and the droplets causes the sensitive condition to shift to higher values of the momentary expansion ratio. The curves outline possible courses of this ratio, for three different rates of expansion. For a relatively low rate, the chamber becomes sensitive only for a brief period; the piston slows down and the chamber becomes insensitive again. For a higher rate, the time of sensitivity becomes longer, but the threshold for condensation on neutrals is still not exceeded at any time. For still higher rates, droplets are first formed only on ions, and then on ions and neutrals. The numerous droplets grow, heating the fluid quickly until once again the chamber comes into a condition suited for formation of droplets on ions alone. All these conditions can be produced at will, but the range of adjustments which gives a long sensitive time for ions without incurring some background at a later time is narrow. An actuating mechanism could be designed which would keep the chamber accurately at a supersaturation suitable for full track development, for a long time after a rapid initial expansion. However, the behavior was good enough to justify postponing this development.

Our inability to avoid background droplets in a certain percentage of the expansions is mainly due to

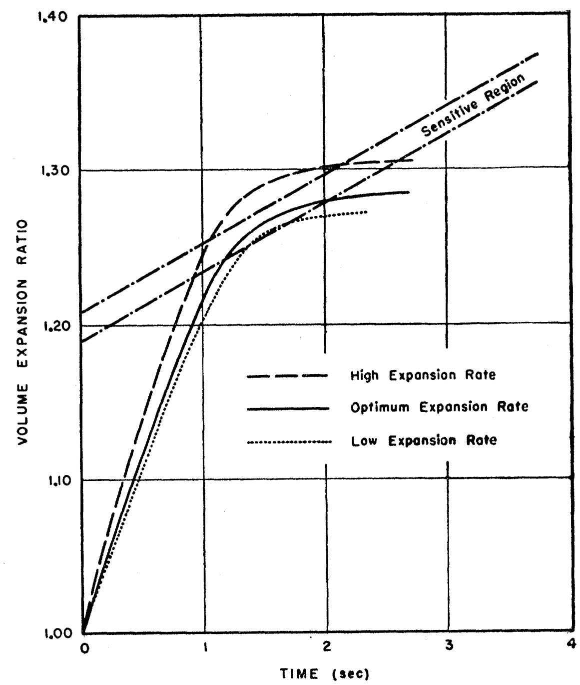

FIG. 3. Volume expansion ratio in a chamber with continued expansion.

(a) slight variations in air-supply pressure, caused by hysteresis of the air-reducer diaphragm; (b) variations in the behavior of valve V; and (c) variations of atmospheric pressure and temperature.

A thorough study of chamber operation was made. Bearden worked with air and water. Since it is rather generally agreed that droplet photography is aided by use of water-alcohol mixtures, we wished to try such mixtures, with various gases. Satisfactory combinations were as follows:

(1) Air, with water and with mixtures of water and ethyl alcohol containing up to 67% alcohol.
(2) Argon, with alcohol-water mixtures containing 67% alcohol.

Carbon dioxide gave unstable results because of its strong absorbability in water. Propane, which was expected to yield an increased sensitive time because of its low ratio of specific heats, gave no tracks, because the range of adjustment was insufficient.

The cycle time was about one minute. A suitable sweep field was kept on continuously to facilitate observation of close ion-pairs on early tracks. Illumination was accomplished with ten 500-watt, 120-volt, 2700°K projection lamps. We employed Corning ultraviolet filters 738 and 385, superimposed.[12] This illumination system gave well-exposed droplet images on 35-mm Tri-X Superspeed Pan at $f/4.5$ with a lens-to-chamber distance of about 57 cm. There were ten

[11] Details are given in the theses of H. C. Fitz, Jr., June, 1955 (unpublished), and W. B. Good, June, 1956 (unpublished), on deposit in the library of the University of Alabama.

[12] Clifford Beck, Rev. Sci. Instr. 12, 602 (1941).

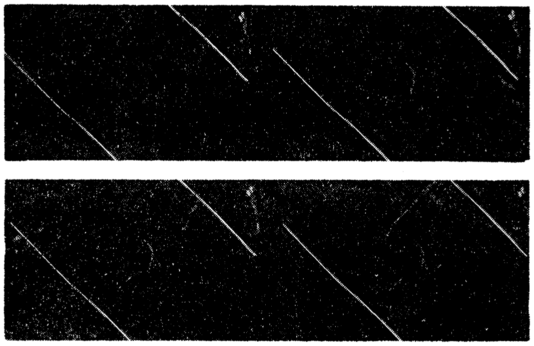

FIG. 4. Illustration of track development. Time increases as we go from left to right and from top to bottom. Note the longest straight track. In the fourth photograph it has fallen into the water-piston. The heavy lines are sweep wires.

exposures per expansion, at intervals of about 0.25 second. The duration of each exposure was $\frac{1}{12}$ second. The photographs were stereoscopic and a variety of devices was available for viewing them.[13] Figure 4 shows the successive entry of tracks, and their growth. Individual track droplets cannot be seen in these reproductions, but some background drops may be perceived. Figure 5 shows regions of vapor poverty in the neighborhood of early tracks, outlined by the absence of drops in the fog which formed later. Attention is called to a vertical cosmic-ray track, showing up as a single bright dot at the center of a circle which outlines the hole in the fog. The diameters of these regions range from about 0.15 to 0.9 cm. The existence of such regions is known to cloud chamber workers through the fact that a late track often shows poor development where it comes close to an early one. The present technique provides a means for study of this phenomenon.

Selection of Photographs for Search

Three criteria for usable photographs will now be outlined.

(*a*) *Low background.*—The sequences were divided into four classes:

1. Underexpansions. Poorly developed tracks.
2. Completely usable sequences. Less than 10 background drops. Tracks grow to full density unless they enter too late.
3. Delayed overexpansions. Part of the sequence shows the desirable characteristics of class 2 but the chamber continues into overexpansion.
4. Overexpansions.

We have utilized only those photographs in which there was no background, or only a few droplets, up to the end of the tenth picture. We could have used the early parts of sequences in which late fog developed, but it seemed best to avoid these borderline cases. It must be remembered that there is not a sharp limit for the onset of condensation on neutral entities. Below a certain supersaturation the formation of droplets on neutrals decreases rapidly. The question now arises, can this method of selection lead to failure to recognize some real subionizers? Suppose for example, that a subionizer was responsible for production of 5 droplets in a photograph containing 10 droplets. In all cases, where several background droplets were present, they were well distributed throughout the chamber volume. If some of them belonged to a track, it would have to be very sinuous. Furthermore, in such cases, we did not see clumps. In spite of these plausibility considerations, it is barely possible that some classes of subionizers were missed. However, our conclusions, stated at the end of this section, refer to the absence of subionizers having substantially straight tracks.

(*b*) *Full development of droplets.*—Tracks fall into the liquid pool, starting from all positions in the chamber, during the long sensitive time. The average duration of a track is 3 photographs, or at least 0.5 second. This agrees well with the average time of fall calculated from Hazen's[14] measurements. This time is long enough for complete development of the droplets, according to his data. When a track first becomes visible, under the conditions of our experiments, the denser clumps of droplets may appear, while images of individuals are too faint to register. In later photographs (excluding the ninth and tenth) the track grows to full development, unless it is so low in the chamber that it falls into the pool before growth is complete. In general, tracks first appear in the third photograph of class 2 expansions. We have considered only those which complete their growth by the eighth photograph, to avoid those affected by turbulence and incomplete growth near the end of the expansion.

Tracks formed after the maximum of supersaturation may fail to develop droplets on ions of both signs. Thus, the track of a fast electron formed at this stage may simulate the track of a subionizer with a charge of about $0.7e$. While such subionizers might be recognized by sufficient study, it is prudent to avoid, for the

TABLE II. Track classification.

Class	Tracks	Duration, sec
1	387	78
2	2687	251
3	2883	221
4	465	51
All	6419	601

[13] One simple device used for preliminary viewing should be mentioned. The film is projected to yield a pair of images about four times original chamber size. The observer sits about halfway between projector and screen with his head just below the projection beam. One eye views both images through a Dove reversing prism and the other eye views them directly. Two three-dimensional images are then seen, and one is simply neglected. Pseudo-stereoscopic viewing is usually employed so that the chamber contents appear to stand out in front of the chamber glass. This seems to result in a psychologic gain.

[14] W. E. Hazen, Rev. Sci. Instr. **13**, 247 (1942).

present, any statement about the occurrence or absence of subionizers with a charge greater than about 0.5e.

Drop counts were made on a representative sample of tracks. The initial and final drop counts agree reasonably well with the figures for primary and probable ionization obtained by earlier workers on electron and meson tracks.

(*c*) *Presence of comparison tracks.*—In examining tracks of suspiciously low ionization, we dealt only with cases in which there were fully developed tracks in the same region. If a suspected subionizer track lay parallel to and close to an earlier track which impoverished the vapor we would have to discount it completely, but this case has not arisen in the body of photographs chosen for definitive study.

With these three criteria a search was made for tracks which appeared, at full development, to show an ionization appreciably less than that of a minimum-ionization electron track. These cases were then subjected to drop-counting under the stereoscopic microscope. They were also examined stereoscopically to verify that the droplets were substantially in a straight line.

Data

The statistics of this experiment, referring to 369 expansions, are as shown in Table II.

On applying all the criteria above, the total sensitive time selected out of the available time in class 2 sequences was reduced to 84 seconds. In this body very few suspicious tracks were found in the preliminary survey. All these were eliminated when drop-count distributions indicated no significant difference from those for relativistic electron tracks.

In addition, we considered whether the sparse background droplets in the class 2 sequences could be due to subionizers of much smaller charge. There were no cases in which three or more droplets of the very sparse background lay even approximately near a straight line.

Discussion

The $\frac{1}{4}$-in. glass wall of the chamber amounts to about 1.6 g/cm^2, sufficient to stop an electron of 3 Mev. For subionizers its effect is smaller. To illustrate the situation, consider a family of subionizers having the electronic mass, but varying charge. The energies which they must possess to have a practical range of 1.6 grams/cm^2 will vary rather like z^2, and are roughly as follows, in Mev:

z:	$\frac{1}{2}$	$\frac{1}{3}$	$\frac{1}{4}$	$\frac{1}{6}$
Energy:	0.8	0.35	0.20	0.089

Thus, million-volt subionizers of the class described, coming from the source, stand a good chance of getting through the glass when z is $\frac{1}{3}$ or less; it is not worth while to present detailed discussion for a variety of values of z, m, and of the initial energy. The point to notice is that in this experiment we may hope to detect a class of relativistic subionizers from the source if they have initial energies of 1 Mev or more. Again, if they are produced in the wall by gamma rays or fast electrons from the source, they should be detectable down to an energy of the same order. For this reason we decided not to use a thin grid-type sidewall to admit particles from the source, although it was available.

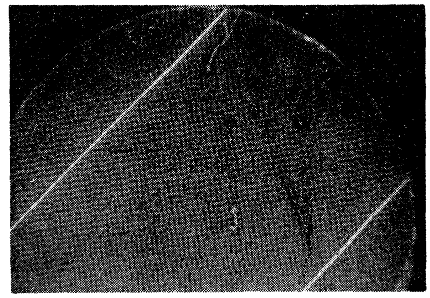

FIG. 5. Illustration of vapor poverty in an overexpanded chamber.

The Poissonian spread of the primary ionization led us to adopt the value 0.5 as a safe upper limit of z, above which uncertainties of interpretation would begin to enter. A lower limit of $\frac{1}{6}$ was adopted since this corresponds to a primary ionization of about 0.33 per cm. For this ionization we can expect about 8 primary ionizations along a track of length equal to the chamber diameter, and consideration of a smaller number, fluctuating severely, would soon lead to difficulties.

Conclusions From Section 5

Examination of photographs containing approximately 2650 tracks, and representing 251 seconds of observation time, has yielded no tracks which could be attributed to charged relativistic subionizers with z in the range $\frac{1}{2}$ to $\frac{1}{6}$. But the three stringent requirements stated above were not entirely satisfied for all these photographs. Therefore, for the purpose of making quantitative statements, we have employed a subgroup containing about 900 tracks recorded in 84 seconds. Most of these tracks were of course Compton electrons.

(a) In 84 seconds there are about 9×10^{10} disintegrations in our source. The solid angle defined by lead shields was 3.9×10^{-5}. Therefore, the number of subionizers per disintegration, of a kind which can get into the chamber, is less than 2.9×10^{-7}.

(b) In 84 seconds about one million hard gamma rays from RaB and RaC strike the wall. Therefore, less than 10^{-6} subionizer is produced by one of these rays.[15]

[15] We take this opportunity to correct our statement in Bull. Am. Phys. Soc. Ser. II, 2, 321 (1957), that this fraction is 10^{-8}. The figure arose from a miscalculation.

6. SEARCH FOR SUBIONIZERS IN THE COSMIC RAYS

A search for subionizers in the cosmic rays was made because the predicted cross section for production of pairs of these particles by photons is large enough to be encouraging and because the great energies available permit processes which would not occur at energies of a few Mev. The nature of the detection problem led us to use a typical cosmic-ray chamber with provision for extending the sensitive time. We decided against counter selection because it might discriminate against some classes of subionizers. The size of the chamber dictated flash illumination. Development of multiple flash equipment did not seem justifiable in a preliminary search, so the question arose whether technique could be developed to search for a finite class of subionizers in a chamber with moderate background, using only one photograph per expansion. This has been done.

Apparatus Characteristics

The apparatus was in a room with about 18 inches of masonry above it, at an altitude of about 250 feet. The chamber was pressure-defined in the compressed condition. There are some special features. To render the gas-motion uniform, a velvet-covered aluminum plate was cemented to the rubber diaphragm. To reduce scattered light a suitable mirror was developed. A parabolic mirror cannot make the light from a finite source parallel, but it was found by ray-drawing that an elliptical mirror properly placed can project a slightly convergent beam through the chamber, keeping it entirely away from two chosen parallel planes and yielding practically uniform illumination throughout. When we used a three-minute cycle with one intermediate expansion, the sensitive time could be increased to about 0.5 second by controlling the time of opening of the expansion valve. However, turbulence begins before the sensitive time comes to an end, so it was expedient to make the exposure about 0.45 second after the beginning of the expansion. This setting corresponds to a useful sensitive time of 0.3 second, because of the time required for reaching appropriate supersaturation and for growth of the droplets.

The photography was carried out at $f/16$, at a distance of 24 in. from the mid-plane. A stereocamera especially adapted to this chamber was built. It was also used as a projector for scanning the film. In order to check events suspected as being subionizer tracks, it was necessary to make drop counts stereoscopically. This was accomplished by rearranging the components of a binocular stereomicroscope.

Ghost Tracks as a Cause of Background

In studying the causes of background, photographs of 834 cyclic expansions, containing about 7000 tracks, were used. The average photograph yielded about one meter of track. The main expansion lasted about 12 seconds and the partial expansion, beginning at 50 seconds, was 24 seconds long. These practices were chosen to encourage removal of droplets by fallout, but they are ineffective in a chamber as high as ours, for reasons now to be explained.

In the absence of effective supersaturation, the distance ions diffuse in one second is of the order of millimeters. When there is sufficient supersaturation, ions are arrested promptly. However, droplets do not grow to the same size in a given time because of competition for vapor and possibly other causes; so they fall at different rates, giving a spread which should not be called diffusion. If an ion-trail were formed long enough before field removal to permit the ions to drift all the way from the front of the chamber to the back, it would have a 90% width of only 6 mm under our conditions. We find that the average width due to the electric field, the diffusion, and the droplet spread is actually much smaller. Therefore, track width is a good criterion for distinguishing the diffuse tracks arising in the current expansion from the much broader ghosts, caused by neutral nuclei. It is commonly believed that these nuclei persist from previous expansions. Except in chambers of relatively small height, the droplets of many tracks evaporate before they reach the floor. There is evidence[16] that some of them do not evaporate completely. It is also possible that some ghosts are due to curious neutral species, formed by fast particles in the long interval between expansions. Eventually it may be possible to remove the nuclei chemically or by a filtration method. Whatever they are, under our conditions they give rise to extra-large droplets which aid us in recognizing the ghosts. The above facts enable us to classify the tracks studied, as follows:

Ghost tracks not affected by the field	2734
Diffuse tracks formed in the current expansion	1444
Undiffused tracks	2328
Heavy tracks (alphas, etc.)	87
Short electron tracks originating in the gas	278

Similar information was not found in the literature. The point to notice is the large number of ghosts, 42% of the first three items. Pileup and diffusion of such debris is considered to be a major cause of the general background in chambers like the one we employed. To illustrate, we had about 6000 ion pairs per expansion. We do not know what fraction of them might give rise, by unknown processes, to persistent neutrals, but since the chamber contains only 27 000 cc the pileup, represented by a geometric series, can be significant.

Use of intermediate expansions is a time-honored method for reducing background. In this work the reduction was not as good as it could have been made by expending more effort, but it brought the background into the range commonly employed by cosmic-

[16] See reference 10, pp. 10–14.

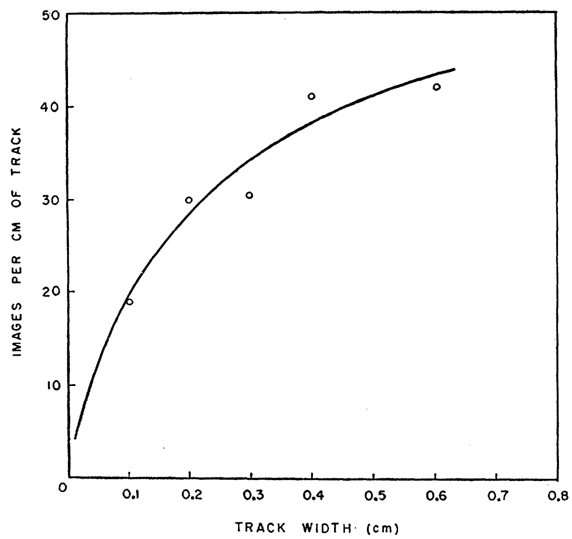

FIG. 6. The number of countable droplets per cm of relativistic electron or meson track as a function of track width.

ray workers. Our observations on ghosts suggest a reason for varying opinions as to the efficacy of intermediate expansions. These expansions are a makeshift expedient.

Precautions in Searching for Subionizers

It is important to understand the development of an ion trail and its visible image so that a very young, poorly developed electron or meson track will not be mistaken for a subionizer. Droplets which condense on the undiffused ions of a trail occurring just prior to photography will have only a limited time to grow. The droplets will be small and those occurring in ion clumps will be very close together. The diffraction images are larger than those of fully developed droplets, and the track appears as a blurred line of faint overlapping images.

The image count is a function of the age and therefore of the breadth of the track. The results of a brief study of this effect are recorded in Fig. 6. It shows that a track suspected to represent a subionizer should not be taken seriously unless it has a width comparable to that which is found sufficient to give the primary specific ionization when we study tracks of ordinary charged particles.

Because the clumps can be used to distinguish a track from a chance arrangement of background droplets, it is desirable to have a qualitative understanding of clump characteristics as a function of track width. Clumps will be the first objects to give well-developed images. Up to a certain age it is impossible to count clumps because there is little contrast between clumps and the rest of the track. They were most easily detected along tracks with a width of about 0.2 cm. There are several reasons for this behavior. As the ion-trail diffuses the smaller clumps dissipate and become obscured, but more of the ions of large clumps give separate images. The net effect is that the clump count passes through a maximum, but the number of images per clump increases steadily with track width, at least up to a width of 0.45 cm. Clump counts and numbers of drops per clump, recorded by one of us, are available to support these statements.[17] For a particle with low z, the primary ionization acts will be well separated and clumps will be easier to recognize than in the case of electron tracks. Nevertheless, it is desirable to restrict attention to tracks whose age is sufficient to reveal droplets of the clumps effectively.

In the light of the considerations above the criteria used in searching for subionizers in the large chamber may be stated:

1. Electron or meson tracks must be available near the suspected track to establish the efficiency of condensation on ions.
2. The suspected track must be at least 8 cm long.
3. The droplet images of the suspected track and the background nearby must be well developed. (One can use the background images in judging whether the track droplets are up to size.)
4. Clumps must exist on the suspected track.
5. On tracks born before full supersaturation was attained, there must be ion pairs. (Background droplets are single.)
6. Tracks should be sufficiently diffused so that the image count gives at least the primary ionization. In our case this means a width of 1.5 mm or more. It is in fact desirable to use tracks so much diffused that the count approximates the probable ionization. For tracks formed before field removal this statement would require appropriate modification.

It is worth noting that when the number of droplets per cc is about four, or more, it is possible to associate the droplets with a track even though they do not fall in a straight line. Under these hypothetical circumstances, we would not be limited to considering relativistic particles. We note that the ionization increases rapidly with a decrease in velocity below the value associated with the minimum ionization. Therefore, particles with charges too small to be detected (for a given background level) at the minimum ionization could be detected at the higher ionization levels associated with smaller velocities. Still lower velocity values might of course give ionization levels indistinguishable from that of ordinary minimum-ionization tracks of electrons and μ mesons. Nevertheless, we have chosen to restrict attention to long straight tracks which could be considered, with good probability, as belonging to relativistic particles.

[17] J. L. Kassner, Jr., Ph.D. thesis, University of Alabama, 1956 (unpublished).

Search for Subionizers

After ruthless rejection of exposures which were in some way substandard, the search for subionizers was conducted on the records of 76 expansions which contained 1125 tracks of all kinds. The average background values can be classified as follows:

0.05 droplet per cc	53 exposures
0.1 droplet per cc	19 exposures
1.0 droplet per cc	4 exposures

Neglecting a few heavy tracks, photoelectrons, etc., the population of events can be divided as follows:

Ghosts	556
Diffused tracks	186
Undiffused tracks	364

Among these, 17 suspected subionizers came to light. By applying the criteria above, all were eliminated. For reasons similar to those in Sec. 5, we conclude that any subionizers with z in the range from $\frac{1}{2}$ to $\frac{1}{4}$ would have been detected. Here the lower limit is set by taking the density of background into account. Purposely, it is made conservative.

Conclusions From Section 6

(a) The ghosts of tracks due to neutral nuclei are present in a cosmic-ray chamber in the proportion of 2 ghosts to 3 fresh tracks. They are a major source of background in such chambers.

(b) In spite of background ranging from 0.05 to 1.0 droplets per cc under various operating conditions, methods have been developed which permit a search for subionizers. Use is made of clumps, the presence of ion pairs, and drop counts, on tracks which have diffused enough to permit employment of these measures.

(c) In photographs containing 550 tracks known to belong to the current expansion, there were 17 suspected of being subionizers. All of these were eliminated.

(d) A conservative statement is that subionizers with z-values in the range $\frac{1}{2}$ to $\frac{1}{4}$ are not present in sea level cosmic rays to an extent as great as one subionizer per 550 tracks.

7. CONCLUDING REMARKS

The achievement of background levels in a Wilson chamber, nearly two orders of magnitude lower than those previously recorded, opens up new avenues. We do not believe we have approached the limit of natural background. It is important to determine whether there are free magnetic poles, and categories of charged particles with masses, charges, etc., well below those of particles now known. It is well not to be dogmatic about such matters since we are only a few decades away from the time when neutrons, positrons, and mesons were unrecognized.

ACKNOWLEDGMENTS

We wish to thank Mr. Milo McEllhiney for efficient construction of apparatus. The work is being continued by students at the University of Alabama under the guidance of Dr. Eric Rodgers. Special thanks are due to Professor J. A. Bearden for the loan of his cloud chamber.

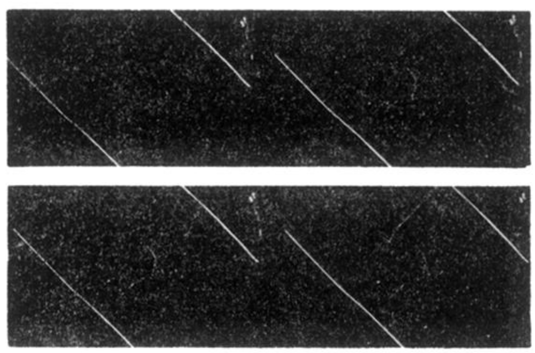

FIG. 4. Illustration of track development. Time increases as we go from left to right and from top to bottom. Note the longest straight track. In the fourth photograph it has fallen into the water-piston. The heavy lines are sweep wires.

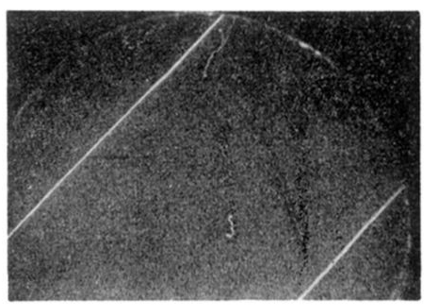

FIG. 5. Illustration of vapor poverty in an overexpanded chamber.