more radical step involving a return to $s=1$ through the choice of a value of λ as high as 0.5 has been referred to above, and necessitates the assumption of two critical latitudes, one of which does not appear, however, at sea level.

Pfotzer, on the other hand, uses a very large value for μ_s, a value equal to 0.85 per meter of water, and he chooses a very large value, 3×10^8 for α, which value he obtains by empirical adjustment to fit the experimental data.

Pfotzer does not place upon his development the requirement of equality of a soft component absorption coefficient above and below the critical latitude. Had he done so, then, quite apart from the magnitude of all of the constants concerned, the logarithmic forms (36) and (37) would have resulted inevitably, and would have demanded the assumption of an upper limit to the primary energy.

Another point of difference between the present paper and that of Pfotzer lies in the fact that in the former we have provided for a variation of intensity with latitude and for a variation of the latitude effect with altitude, which phenomena placed very stringent requirements upon the theory. Pfotzer obtains the sea-level altitude effect from the hard component, but does not provide for an increase of latitude effect with altitude.

Pfotzer attributes the maximum in the intensity-altitude curve to a range phenomenon of the secondaries and determines from it the secondary range at these altitudes. In this, his conclusions are substantially similar to those which I have reported here and on various former occasions,[18] the calculated range being equivalent to about 82 centimeters of water.

In conclusion, I wish to express my appreciation of the services of Dr. and Mrs. C. G. Montgomery who have given me considerable assistance, necessitating careful discrimination, in the numerical calculations, and who have checked the mathematical calculations.

[18] W. F. G. Swann, "Cosmic-Ray Measurements." Presented at Washington, May 1, 1935, as part of a symposium on the 1935 National Geographic U. S. Army Air Corps Stratosphere Flight. See also W. F. G. Swann, G. L. Locher, W. E. Danforth, C. G. and D. D. Montgomery, National Geographic Society Contributed Technical Papers, Stratosphere Series, No. 2 (1936).

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Cosmic Rays as Electrical Particles*

Arthur H. Compton, *University of Chicago, Chicago, Illinois*

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Positive evidence that the primary cosmic rays consist of electrical particles is drawn from three types of experiments:

1. **Latitude and directional asymmetry effects.** Clay finds 83 percent as intense ionization at the equatorial minimum as in high latitudes. Of the remainder, Rossi's directional experiments show that about 12 percent at least is due to positively charged particles. Corresponding to the 73 percent "nonfield sensitive" remainder at sea level, at high altitudes the remainder must be less than 20 percent, perhaps no more than 2 percent, of that observable in polar regions. An energy distribution analysis, following the method of Zanstra, but using new latitude effect data collected on the Pacific Ocean in collaboration with R. N. Turner, shows a continuous energy distribution of the primary cosmic-ray particles between 0.9 and 1.9×10^{10} ev, and indicates the electrical particle origin of a large part, very possibly the whole of the ionization.

2. **Coincidence experiments.** Auger, Street and their collaborators have proved that most of the multiple coincidences observed with counter tubes are caused by single high energy ionizing (hence electrical) particles. Experiments by Rossi and Hsiung show that these coincidence producing particles are not secondaries, but originate beyond the atmosphere. Likewise latitude effect experiments by Johnson and absorption experiments by Rossi indicate that the shower producing radiation is produced by electrical primaries. Cloud chamber studies show that almost all of the observed cosmic-ray ionization is due either to particles of the coincidence type or to showers, and is hence ascribable to electrical primaries.

3. **Galactic rotation effect.** A directional asymmetry of cosmic rays ascribable to the motion of the earth with the rotation of the galaxy, seems to be established by sidereal time variations very recently reported for the northern hemisphere by Illing and for the southern hemisphere by Schonland, Delatizky and Gaskell, and by a new provisional observation by Compton and Turner of a difference of 0.6 percent between the northern and southern

* Based upon a paper delivered at the Tercentenary Conference of Arts and Sciences at Harvard University, September 8, 1936.

hemispheres. These results are in quantitative agreement with the approximate predictions of Compton and Getting based upon electrically charged primaries; but the observed diurnal effect is only about 1/7th as great as is to be expected if the primary cosmic rays are photons. The data are thus difficult to reconcile with more than a few percent of primary photons.

Two lines of positive evidence for photon primaries have been put forward. 1. The flattening of the altitude *vs.* ionization curves at very high altitudes, once interpreted as indicating the gradual growth of secondary ionization as primary photons enter the atmosphere, has been shown by later balloon flights at different latitudes to be a geomagnetic phenomenon, indicating that the corresponding portion of the radiation is electrical in character. 2. Certain high energy nonionizing shower producing rays shown in cloud photographs by Anderson and his collaborators have been ascribed to primary photons. A more detailed examination of the photographs in question, however, seems to show that these shower producing rays are definitely of local and hence secondary origin. The arguments that have been raised by Bowen, Millikan and Neher against the explanation of cosmic-ray ionization as due to electrically charged primaries are all found to have a straightforward answer if we assume the correctness of current theories which make photon production the chief mechanism whereby a cosmic-ray electron loses its energy. The conclusion is drawn that primary photons are not responsible for any of the major features of the cosmic rays as we now know them. It seems necessary to assume the presence of both positive and negative electrons among the primaries. There is also some suggestion of the existence of protons.

IN several recent addresses[1] I have presented evidence which seemed to justify the conclusion that cosmic rays consist almost exclusively of electrically charged particles, and that electrically neutral primary rays, if present, are responsible for so small a fraction of the observed cosmic-ray effects as to be indistinguishable by our present experiments. A similar view has been expressed also by many others.[2] More recent data have seemed to me only to reinforce this position. There have however been put forward from time to time weighty arguments[3–6] for the contrary view that the major part of the cosmic rays is electrically neutral. As far as I am aware, no attempt has been made to answer these arguments in detail. It is my purpose in this paper to review the evidence in light of our present knowledge, and to attempt to reconcile the data that have been presented.

Permit me first to present the positive evidence that electrically charged particles constitute the major part of the primary cosmic rays:

1. Evidence from the Latitude Effect

It is well recognized that the geographical variations in cosmic rays follow the earth's magnetic field so closely that the effect must be a magnetic one. This means that a significant component of the cosmic rays observed near sea level is due to electrically charged primaries; for it has been shown[7–9] that the geographical effect is quantitatively explicable on this basis according to the theories of Störmer[10] and Lemaitre-Vallarta,[11] whereas it cannot be explained in terms of the effect of the earth's magnetic field on secondary electrical particles produced in the atmosphere.[7, 12, 13] The question remains as to what fraction of the observed cosmic-ray effects owes its origin to such electrically charged rays.

Three typical values of the magnitude of the sea-level latitude effect are Clay's datum[2d] of 17 percent reduction with an unshielded chamber between 45° and 0° magnetic latitude, my own figure of 14 percent with a 6 cm lead shield,[14] and Millikan and Neher's value[9] of 12.5 percent with

[1] a. Guthrie Lecture of the Physical Society, Feb. 1, 1935. Proc. Phys. Soc. London **47**, 747 (1935). b. American Philosophical Society Address, Apr. 20, 1935. Proc. Am. Phil. Soc. **75**, 251 (1935). c. Address before American Physical Society and Section B of AAAS, Jan. 1, 1936. Rev. Sci. Inst. **7**, 71 (1936).

[2] E.g., (a) W. Bothe and W. Kolhörster, Zeits. f. Physik **56**, 751 (1929); (b) B. Rossi, Zeits. f. Physik **82**, 151 (1933); Proc. London Conference on Nuclear Physics **1**, 233 (1935); (c) W. Kolhörster, Physik Zeits. **34**, 809 (1933); (d) J. Clay, Proc. Roy. Soc. **A151**, 202 (1935); (e) T. H. Johnson, Carnegie Inst. Supp. Pub. No. 13 (1935); (f) P. Auger, Comptes rendus **200**, 739 (1935); (g) P. M. S. Blackett, *La Radiation Cosmique* (Hermann & Cie., 1935).

[3] H. Kulenkampff, Physik Zeits. **30**, 561 (1929).

[4] Regener, Kramer and Lenz, Zeits. f. Physik **85**, 411 and 435 (1933).

[5] I. S. Bowen, R. A. Millikan and H. V. Neher, Address before London Conference on Physics, October, 1934. (London, 1935), p. 206. Also in Phys. Rev. **46**, 641 (1934).

[6] R. A. Millikan, paper before National Academy of Sciences, Apr. 28, 1936 (unpublished).

[7] A. H. Compton, Phys. Rev. **43**, 87 (1933).

[8] J. Clay, Physica **1**, 363 and 829 (1934).

[9] R. A. Millikan and H. V. Neher, Phys. Rev. **47**, 205 (1935).

[10] C. Störmer, Zeits. f. Astrophysik **1**, 237 (1930).

[11] G. Lemaitre and M. S. Vallarta, Phys. Rev. **43**, 87 (1933).

[12] I. S. Bowen, Phys. Rev. **45**, 349 (1934).

[13] P. M. S. Blackett, reference 2 (g), p. III–18.

[14] A. H. Compton, Trans. Am. Geophys. Union (1933), p. 154.

a 12 cm shield. Of these, Clay's value of 17 percent is to be preferred for our present purpose. This fraction is known to be due to electrically charged primaries, leaving 83 percent to be accounted for.

That a part of the remainder is electrical is established by directional experiments, made with coincidence counting tubes, which show that the rays reaching the earth at the equator come mostly from the west.[15] This, like the latitude effect, is due to the action of the earth's magnetic field, and shows an excess of positively charged particles. At a zenith angle of 45°, having filtered out the soft secondaries with 8 cm of lead, Rossi[15c] finds near the equator 0.76 as many rays from the east as from the west. For these equatorial rays, therefore, at least 24 percent of those incident at 45° west, or about 12 percent of those incident vertically, are due to positively charged primaries. Taking this 12 percent as a reasonable average, there thus remain $0.83\times0.88=73$ percent as an upper limit to be accounted for,[16] the remaining 27 percent having been proved electrical.

An energy distribution analysis based upon the latitude effect shows that these magnetically deflectable rays constitute a portion of what appears to be a continuous energy spectrum. Zanstra has pointed out[17] that, since there is a definite lower limit V_0 imposed by the earth's magnetic field upon the energy of the rays reaching the earth vertically at each latitude, a measurement of the latitude effect for such vertical rays should give their energy spectrum. If $\phi(V)dV$ is the ionization due to the vertical rays having energies between V and $V+dV$, Zanstra shows that

$$\phi(V)dV=-(d\psi/dV_0)dV, \tag{1}$$

where ψ is the observed ionization due to the vertical rays, and V_0 is the lower limit to the energy of the transmitted electrons, which, expressed in electron volts, is*

$$V_0=1.92\times10^{10}\cos^4\lambda, \tag{2}$$

λ being the geomagnetic latitude.

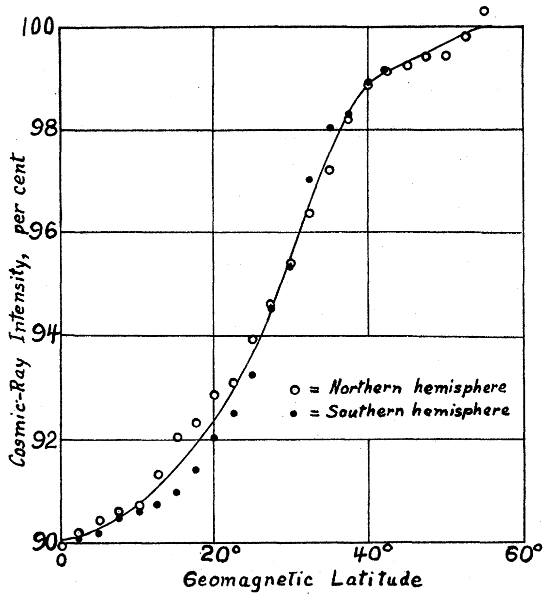


FIG. 1. Latitude effect between Vancouver and Sydney, expressed in percent. Mean of 4 voyages (Compton-Turner, 1936).

Though latitude effect measurements on the vertical rays have been made with coincidence counting tubes,[18] the observations have statistical errors which are too great to be suitable for such an analysis. Measurements of the distribution of cosmic rays with varying zenith angle show, however, that their angular distribution is within experimental error the same at different latitudes.[19] Accordingly, ionization measurements which average the intensity from all zenith angles should give very approximately

[15] E.g., (a) T. H. Johnson, Phys. Rev. **43**, 834; **44**, 856 (1933); (b) L. Alvarez and A. H. Compton, ibid. **43**, 835 (1933); (c) B. Rossi and S. de Benedetti, ibid. **45**, 214 (1934).

[16] Using the data from their own latitude effect and Korff's directional effect measurements in America, Bowen, Millikan and Neher, reference 5, calculate this remainder on a similar basis as 0.85.

[17] H. Zanstra, Naturwiss. **22**, 171 (1934).

* *Note added in proof:* The value of V_0 is given more exactly by the recent calculations of Lemaitre and Vallarta (Phys. Rev. **50**, 493 (1936), Fig. (10). The difference from Störmers formula (2) is however not sufficient to modify the conclusions here reached.

[18] a. P. Auger and L. Leprince-Ringuet, Nature **133**, 138 (1934); b. J. Clay, Physica **2**, 299 (1935).

[19] Among the best published results are those of Johnson, reference 20, in Peru (equator), and of Kolhörster and Janossy, reference 21, in Germany. They find, respectively, for the ratio of the intensity at zenith angle 45° to 0° the values 0.475 and 0.495, each with a probable error of about 1 percent. Auger and Leprince-Ringuet, comparing this ratio at latitudes 0° and 38° with somewhat lower precision, find a slight difference in the opposite sense.

[20] T. H. Johnson, Phys. Rev. **45**, 584 (1934).

[21] W. Kolhörster and L. Janossy, Zeits. f. Physik **93**, 111 (1934).

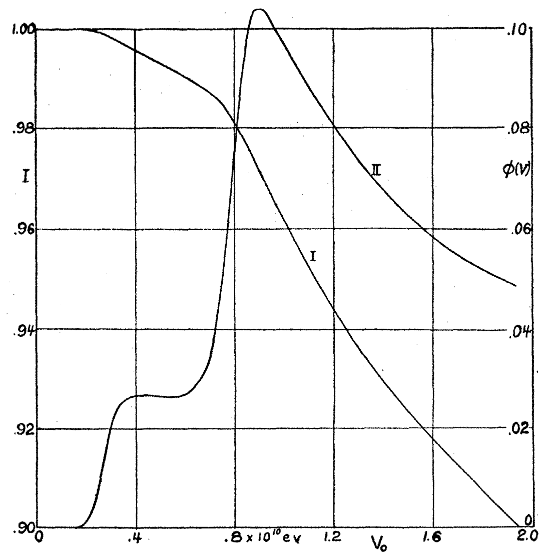


FIG. 2. Curve I represents data of Fig. 1 plotted against the geomagnetic energy minimum V_0. Curve II is the slope of curve I, and represents the energy spectrum of the rays (assumed to be electrons) transmitted by the atmosphere.

the relative values for the vertical component of the rays. We may thus use in place of Zanstra's Eq. (1),

$$\phi(V) = -dI/dV_0, \tag{3}$$

where I is the cosmic-ray intensity as observed with an ionization chamber.

Thanks to the courtesy of the Canadian Australasian Steamship Company, Captain Hill of the *R.M.S. Aorangi*, and especially the very skillful help of First Officer R. N. Turner, we have been able to obtain a series of repeated measurements of the latitude effect over the route from Vancouver, Canada, to Sydney, Australia, using one of the Carnegie Institution's model C meters[22] shielded with 12 cm of lead. The results of 4 trips are shown in Fig. 1, and represent the most suitable data for our modified Zanstra analysis which are now available. Recalling that each geomagnetic latitude corresponds to a given energy minimum V_0, these data may be averaged and plotted against V_0, as in curve I of Fig. 2. For energies lower than 0.2 the curve is drawn flat, in accord with Clay's result that north of $\lambda = 54°$ no change as great as 0.6 percent occurs.[23] When the slopes of this curve are taken, we obtain from Eq. (3) the values of $\phi(V)$ shown in curve II.

For values of V_0 below 0.9×10^{10} the effect of the earth's atmosphere becomes evident in limiting the rays that are received to a higher energy than the minimum admitted by the

[22] Cf. A. H. Compton, E. O. Wollan and R. D. Bennett, Rev. Sci. Inst. **5**, 415 (1934).

[23] J. Clay, C. G. t'Hooft and P. H. Clay, Physica **2**, 1033 (1935).

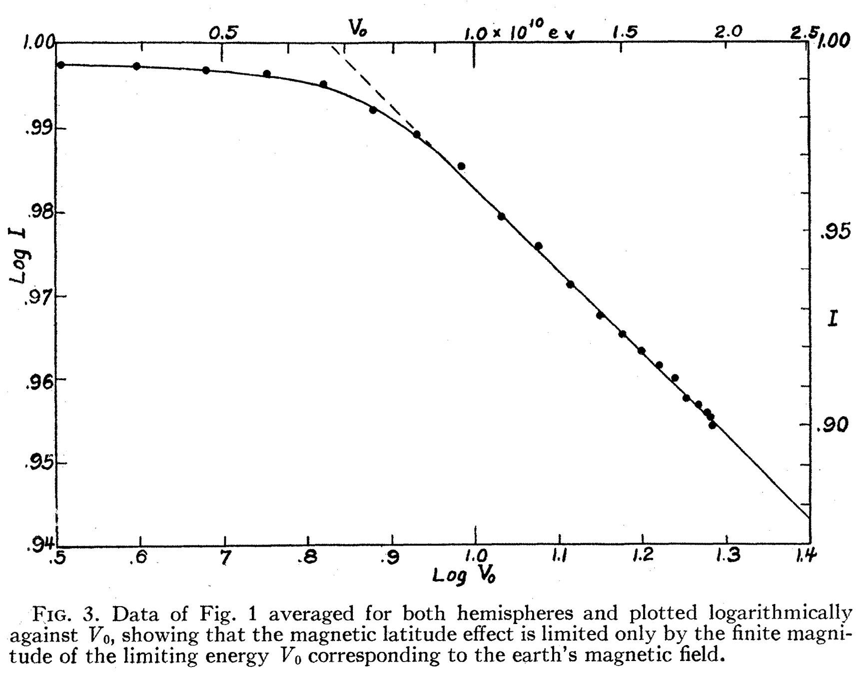


FIG. 3. Data of Fig. 1 averaged for both hemispheres and plotted logarithmically against V_0, showing that the magnetic latitude effect is limited only by the finite magnitude of the limiting energy V_0 corresponding to the earth's magnetic field.

magnetic barrier. The form of the curve for the lower energies strongly suggests two components, one with a limiting energy imposed by the atmosphere of about 8×10^9 ev ($\pm$electrons?) and the other of about 2.5×10^9 ev (protons?). There are several lines of evidence supporting this interpretation. It will, however, be preferable to postpone discussion of these interesting details until the further data now being collected are available.

For our present purpose the important point is that for energies over 0.9×10^{10} ev, where the atmospheric absorption is not a determining factor, there appears a continuous energy distribution as far as 1.92 ev, beyond which the method is no longer applicable.[24] The trend of the curve indicates, however, that electrical particles of much higher energies are present in considerable quantity.

In order to extrapolate to higher energies, a more suitable representation of the data is to plot log I against log V_0, as in Fig. 3, where the points represent the average measured intensities. For energies greater than 0.9×10^{10} ev it will be seen that the points fall within experimental error upon a straight line. If this line were to continue indefinitely, it would mean that for infinite limiting energy V_0 the percentage of transmitted cosmic rays I would be zero, i.e., all the cosmic rays would be proved electrical. In other words, this quantitative analysis indicates that the magnitude of the latitude effect is limited only by the strength of the earth's magnetic field, and if that field were very great, the cosmic rays might well be completely excluded near the equator.

The latitude effect at high altitudes has not been studied in sufficient detail to carry through a similar analysis. Its rapid increase with altitude is however well known. Fig. 4 shows typical results of recent high altitude measurements. Millikan and Neher have recently reported[6] that their airplane flights in the Philippines give results closely similar to those here shown for Peru, whereas Clay's values in Java are presented with reservations. These data indicate a ratio near the top of the atmosphere of at least 4 to 1 between 52° and the equator. There seems also little question but that near the poles the intensity at great altitudes should be considerably greater than at 52°.[25] Moreover, as in the case of the latitude effect at sea level, directional experiments show that much of the rays reaching the equator must be electrical. We may accordingly conclude that of the cosmic-ray ionization at very high altitudes, not more than a few percent can be due to neutral primaries.

2. Evidence from Coincidence Experiments

Perhaps the most striking proof that the coincidences observed with multiple counters in line are due to single high energy particles traversing them all is supplied by the recent experiment performed independently by Auger and Ehrenfest[26] and by Street, Woodward and

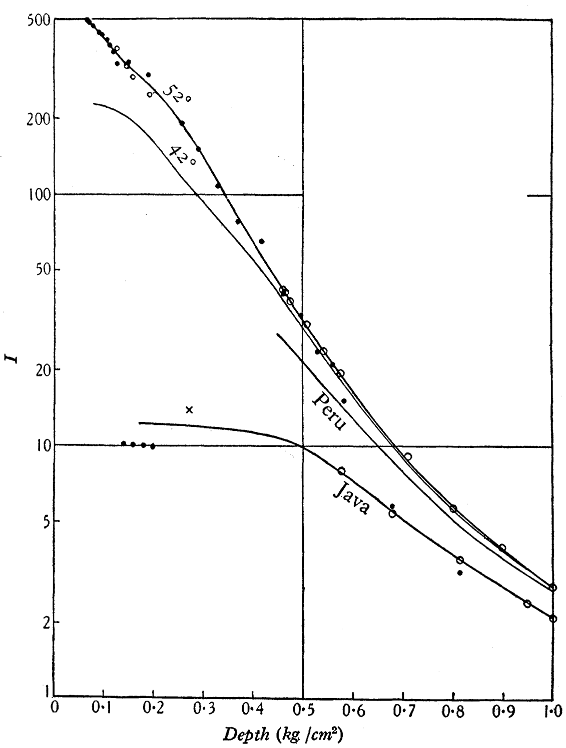


Fig. 4. High altitude measurements of cosmic rays at different latitudes. 52°, Compton-Stephenson-Millikan; 42°, Millikan-Bowen; Peru, Millikan-Neher; Java, Clay.

[24] This conclusion is similar to that reached by Clay, reference 18 (b), from his latitude effect experiments with counter tubes.

[25] Cf., however, *M.* Cosyns, Nature **137**, 616 (1936), whose balloon flights suggest that the latitude effect at high altitudes may end sharply at geomagnetic latitude 49° in Europe.

[26] P. Auger and Ehrenfest, Comptes rendus **199**, 1609 (1934).

Stevenson,[27] and illustrated in Figs. 5 and 6. Cloud photographs are taken when 3-fold coincidences are produced by rays traversing 45 cm of lead. With this arrangement, 90 percent of the photographs record single straight tracks. This is clear evidence that such coincidences are produced by highly penetrating particles. Experiments by Rossi[28] have shown that about half of these particles will penetrate a lead screen equivalent in mass to the atmosphere, which is about the same rate of absorption as is observed with the cosmic rays as measured by an ionization chamber. This strongly suggests that the penetrating particles are the primary cosmic rays, a confirmation of Bothe and Kolhörster's classical argument.[2a]

Rossi[2b] and Hsiung[29] have performed in different forms an experiment which shows that these penetrating particles are not secondaries producible at sea level, but must come from far above the apparatus. Thus in Fig. 7, if penetrating secondaries were excited in 20 cm of lead, the counts with arrangement C should be greater than in case B. After making allowance for the

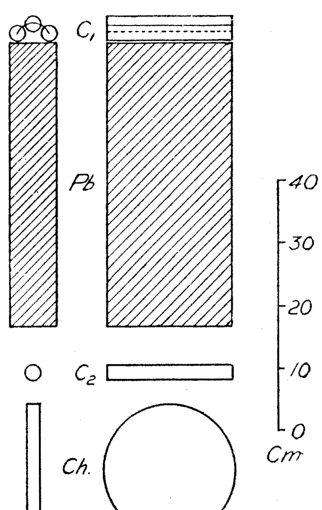


FIG. 5. Arrangement of coincidence counters, C_1, C_2, C_3 and expansion chamber *Ch* for photographing trails of penetrating cosmic rays (Street-Woodward-Stevenson).

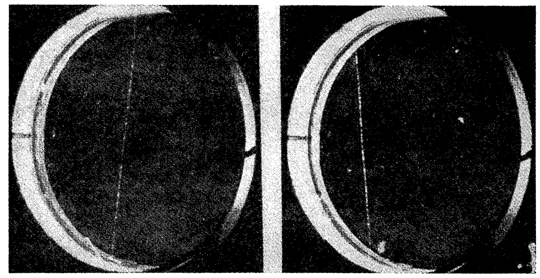


FIG. 6. Trails of two cosmic-ray particles after traversing 40 cm of lead (Street-Woodward-Stevenson).

slight effect of the well-known soft secondary rays, both Rossi and Hsiung find the coincidence rate in cases B and C identical within experimental error. Thus all the coincidence producing particles originate above the apparatus.

It might be supposed that these penetrating particles are, however, secondaries excited high in the atmosphere by readily absorbable photons. This suggestion is ruled out by two facts. (1) The coincidence producing particles have been found to show the latitude effect in substantially the same way as does the total cosmic-ray ionization,[18] and also to exhibit directional asymmetry in the earth's magnetic field at the equator.[15] They are thus at least in large measure due to high energy primary electrical particles, and our knowledge of their high penetrating power can leave little doubt but that they are themselves these primary particles. (2) We shall see below that very high energy photons and electrons of the same energy should be absorbed at approximately the same rate. Thus if the high energy coincidence producing electrons are due to primary photons, some of these photons should penetrate the atmosphere, in intensity comparable with the secondary electrons, and excite more high energy electrons in the lead block of the Rossi-Hsiung apparatus. That this does not occur may be taken to mean that the fraction of the coincidence producing particles which are secondaries of high energy photons is zero, with a probable error of about 3 percent.[30]

In addition to these coincidence producing particles, a "shower producing radiation" is like-

[27] J. C. Street, R. H. Woodward and E. C. Stevenson, Phys. Rev. **47**, 891 (1935).
[28] B. Rossi, Naturwiss. **20**, 65 (1932); Zeits. f. Physik **82**, 151 (1933).
[29] D. S. Hsiung, Phys. Rev. **46**, 653 (1934).

[30] If, as Bowen, Millikan and Neher assume, the photons are much more penetrating than the electrons of the same energy, this argument becomes the more cogent; for the conditions for producing high energy electrons in the lead block are then ideal.

wise recognized.[31] This may be studied either with counting tubes out of line, or with a cloud chamber. The evidence strongly favors the view that this shower producing radiation consists of high energy photons. Johnson[31c] has shown, however, that this radiation also is subject to latitude effect, which means that the photons must themselves be produced by primary electrical particles.[32] It would appear that nearly all of the cosmic-ray tracks observed in cloud chambers are of either the high energy coincidence producing type or the shower type. Since both of these are ascribable to primary electrical particles, very little room is left for any ionization that may result from primary photons.

It should be added that cosmic rays in deep mines are measurable with multiple coincidence counters, which, as Kolhörster and Clay have pointed out,[2] means that the rays there observed are corpuscular in the same sense as are those at sea level.

3. Evidence from the Translational Effect

There is a third type of evidence regarding the nature of the primary cosmic rays which comes from the magnitude of the effect on the intensity of cosmic rays due to the earth's rapid motion with the rotation of the Milky Way. The experimental data are now adequate to state with considerable confidence that this effect exists, and is of the magnitude predicted upon the assumption of electrically charged rays. The observed effect is, however, much too small to fit the prediction based upon photons as the primary rays.

It will be recalled that according to the astronomers' recent findings the rotation of the galaxy carries the earth in the direction of the constellation Cygnus, about 45° north, at a speed of about 0.001 that of light. For rays such as cosmic rays going with approximately the speed of light, this produces a Doppler effect difference in frequency of 0.2 percent between the rays striking the front and the back of the earth, if the origin of these rays is assumed to be at rest outside of the galaxy. The corresponding Doppler effect in intensity at the surface of the atmosphere would be 4 times as great, or 0.8 percent. When account is taken of the absorption by the atmosphere, and the fact that the measurements, being made with an ionization chamber, include rays from all angles, Dr. Getting and I calculate about 1.0 percent difference between the front and the back of the earth.[33] This, of course, assumes that if the earth were not moving the intensity would be the same from all directions.

If the primary cosmic rays consist of photons or other neutral particles, this full effect should be observed. If they are electrically charged, according to Störmer's theory the particles will be so strongly deflected by the earth's magnetic field that the effect will be much reduced. A comparison of the predicted and the observed

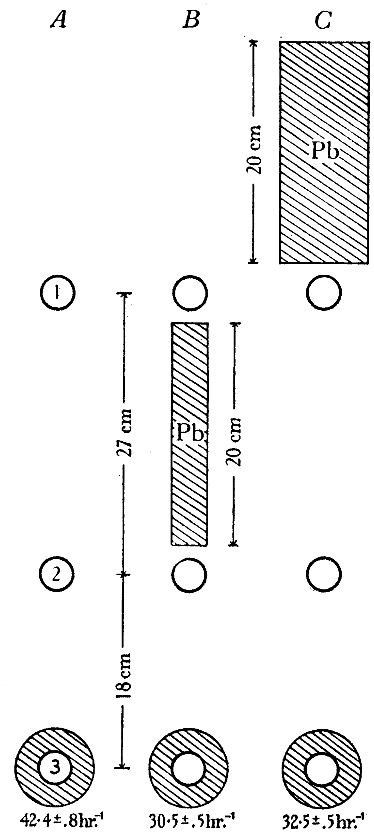


Fig. 7. Hsiung's coincidence experiment.

[31] (a) Cf. B. Rossi, reference 2 (b); (b) C. D. Anderson, R. A. Millikan, S. Neddermeyer and W. Pickering, Phys. Rev. **45**, 352 (1934); (c) T. H. Johnson, Phys. Rev. **47**, 318 (1935).

[32] Rossi (reference 2 (b)) reaches the same conclusion on the basis of absorption measurements.

[33] A. H. Compton and I. A. Getting, Phys. Rev. **47**, 817 (1935). The value there predicted is 1.2 percent difference between the front and the back of the earth. The slightly lower value here given involves a minor correction to our published calculation.

TABLE I. *Test of the translational effect.* Percent variations.

	Theory		
	Photon Primaries	Positron Negatron Primaries	Experiment
Latitude 47°N			
Amplitude of diurnal variation	0.25	0.02–0.10	0.03+
Phase of diurnal variation	20h 40m	20h 40m	20h 50m
Latitude 34°S			
Amplitude of diurnal variation	0.28	0.03–0.12	0.04×
Phase of diurnal variation	20h 40m	20h 40m	21h 45m
N – S Difference	0.5	0.5	0.6=

+ Triennial mean, Illing.
× Triennial mean, Schonland, Delatizky and Gaskell.
= Provisional value, Compton and Turner.

values is shown in Table I for both the assumption of photon primaries and of positron-negatron primaries. This table shows the data that have been reported within the last few months. It may be noted that whereas the effect calculated for electrical particles is rather uncertain because of the unknown magnitude of the geomagnetic effect, if the cosmic rays are photons the only escape from an effect of about the predicted magnitude would seem to be the difficult assumption that there occurs a natural anisotropy in the source of the rays just sufficient to balance the translational effect.

A suggestive confirmation of the prediction was immediately possible using data obtained by Hess and Steinmaurer during the year 1932. Since that time Illing[34] has published, in June of this year, a reduction of Hess' measurements for the three years 1932, 1933 and 1934, corrected for barometer changes and plotted against sidereal time. The result, as indicated in the first row of Table I, shows a variation with precisely the predicted phase, and with an amplitude which lies within the range estimated for electron cosmic rays, though only 12 percent of that calculated for photon rays.

Illing left the existence of the effect open to some experimental doubt, because of possible seasonal variations. Just now, however, a similar summary of three years' measurements in the southern hemisphere has appeared, by Schonland and his collaborators at Capetown,[35] which shows an effect of the same order of magnitude and with almost exactly the same phase. This disposes of any possibility of a seasonal variation, since this should be opposite in phase in the two hemispheres. We may thus consider the galactic rotation effect to be real, and its magnitude to fit the rough estimates based upon the electron hypothesis of cosmic rays.

Our studies of the intensity of cosmic rays on the Pacific Ocean should eventually give us a good experimental value of the difference in intensity between the northern and southern hemispheres. As yet our results are only provisional, because the southern end of the journey is not far enough south to reach the polar plateau of cosmic-ray intensity. Basing our estimate, however, upon the observed intensity at the first knee in the northern and southern curves, we find a greater intensity in the north by about 0.6 percent—very close to the theoretical difference.

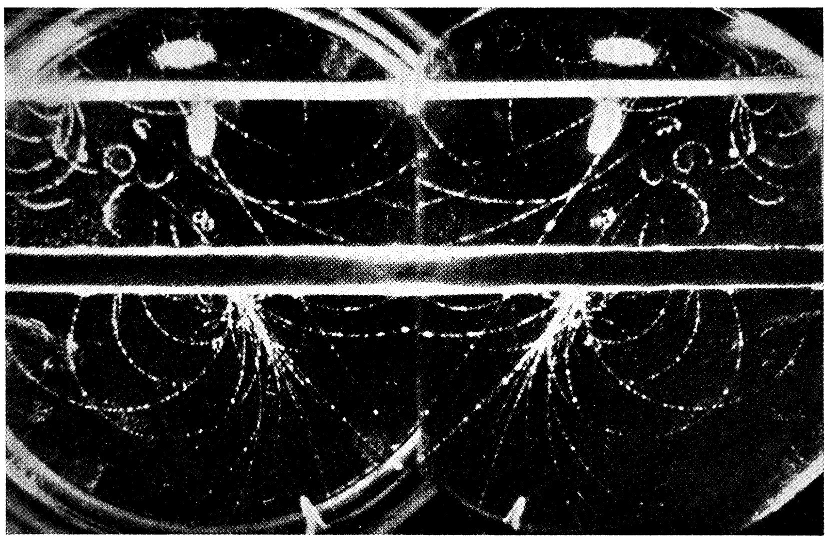
This tentative verification that the translational effect is of the full magnitude given by the theoretical calculation makes it very difficult indeed to reconcile the small diurnal variation with the assumption that photons constitute more than a few percent of the primary cosmic rays.

4. ARGUMENTS FOR PRIMARY PHOTONS

The most effective defense of the hypothesis of primary photons which has come to my attention is that of Bowen, Millikan and Neher,[5] presented before the London Congress of Nuclear Physics in 1934. They admit the electrical character of the primary rays responsible for about 15 percent of the ionization observed at sea level, as shown by latitude effect and directional experiments. They however consider practically the whole of the remaining "nonfield sensitive" portion, estimated as responsible for 85 percent of the sea-level ionization, to be due to primary photons. More recent statements by Professor Millikan[6] indicate that this view has remained essentially unaltered.

[34] W. Illing, Terr. Mag. and Elec. June (1936).

[35] B. F. J. Schonland, B. Delatizky and J. P. Gaskell, Nature **138**, 325 (1936).



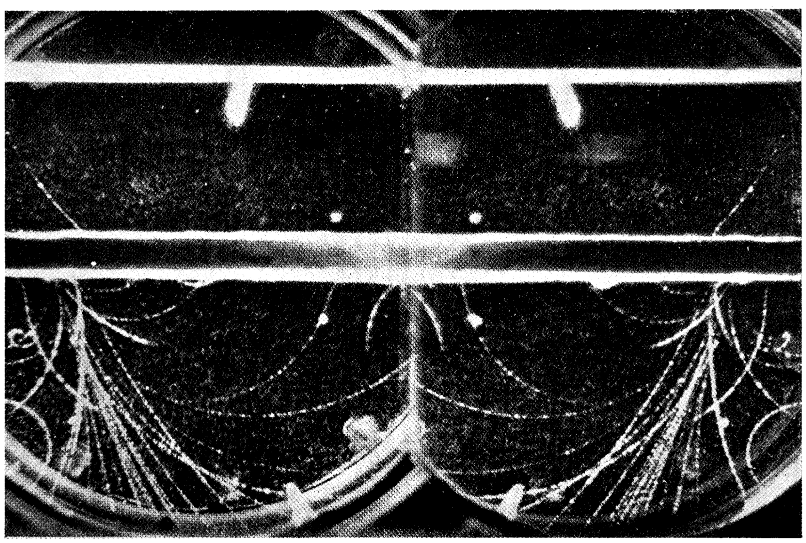


FIG. 8 AND FIG. 9. Cloud photographs of showers (Anderson, Millikan, Neddermeyer, Pickering) that have been used as evidence of incoming primary photons. The showers are interpreted in the text as due to secondary photons.

(1) The one positive argument put forward for primary cosmic-ray photons is the citation[5] of two of Anderson's cloud photographs, Figs. 8 and 9, which show showers of positrons and negatrons that must have been produced by photons having in some cases total energies exceeding 2.5×10^9 ev.[36] "There seems to be no escape," they comment, "from regarding these showers as resulting from incoming photons themselves."

[36] Cf. reference 31 (b), Figs. 9 and 11.

We would suggest the alternative interpretation that the photons which produce these showers are themselves secondaries from an event which occurred not far above the cloud chamber. In Fig. 8 we note that at least two of the showers, the high energy pair from the top of the chamber and the large shower from the central lead plate, have total energies of the same order of magnitude, $>5\times 10^8$ ev. If it is assumed that these are caused by the same photon in

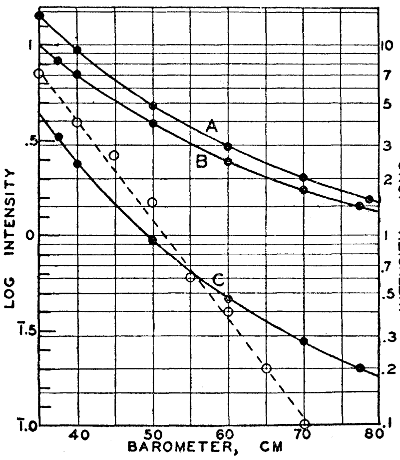


FIG. 10. Cosmic-ray intensity *vs.* latitude curves for, *A*, high magnetic latitudes, *B*, magnetic equator, *C*, difference between *A* and *B*, showing that equatorial rays *B* are absorbed in the same manner as are the magnetically deflectable rays *C* (Compton and Stephenson).

successive ionizing events, it indicates a rate of absorption much too great for a ray which can penetrate the atmosphere. If on the other hand they are due to different photons, their identity in time and direction and their small lateral separation shows that these photons must have originated in the same event not far above the chamber. In either case their secondary origin appears to be necessary. Similarly an examination of Fig. 9 shows at least 3 points of origin of the showers, close together in the central plate. Two of these showers are of the same large order of magnitude of energy. Their direction shows that no one can be considered as the parent of the others; it is clear that they are all due to a close bundle of nearly parallel, non-ionizing rays, presumably photons. Their close proximity indicates that their origin must have been only a short distance above the expansion chamber. Here also a secondary origin of the photons is therefore clearly indicated. The evidence presented for the occurrence of primary photons is thus unsatisfactory.

(2) All the remaining arguments are attempts to show that incoming electrical particles are incapable of producing the observed cosmic-ray effects. Thus Bowen, Millikan and Neher state that the absorption of the high energy electrons "cannot possibly yield an altitude ionization curve remotely resembling that found experimentally from sea level up to 4.5 m." This they emphasize as "the most general and the most cogent argument against the attempt to explain the nonfield sensitive portion of the cosmic-ray ionization as due primarily to incoming high energy electrons." They suppose rather that absorption of such high energy electrons should be of the "range" type instead of the "exponential" type. Such arguments are ineffective when it is recognized that the main part of the energy loss by high energy electrons is through the production of photons (as x-rays are produced by cathode rays), and that this type of energy loss leads necessarily to an approximately exponential diminution of ionization along the path of the electrons.

That high energy electrical rays are in fact absorbed exponentially was shown some years ago by our high altitude measurements of cosmic rays at different latitudes.[37] Thus in Fig. 10, curve *A* represents the absorption in the atmosphere of the rays received at high magnetic latitudes, and *B* that of the rays at the equator. Curve *C* is the difference between *A* and *B*, and thus shows the absorption of electrically charged rays of the type so affected by the earth's magnetic field that they cannot reach the earth at the equator. The close similarity of curve *C*, which includes only electrically charged rays, to curve *B*, which represents the rays transmitted by the earth's field at the equator, shows that electrically charged particles are absorbed in the manner characteristic of cosmic rays. As is well known, a curve of type *C*, being concave upwards, is expressible as a spectrum of exponentially absorbed components. In order to fit this curve the values of the absorption coefficients would need to extend at least from 0.035 to 0.12 per cm of mercury, corresponding to the electrical particles, perhaps of different natures, included in the energy range of from 2×10^9 to 2×10^{10} ev. This would seem to be an adequate answer to the argument against primary electrons quoted above.

According to Bethe and Heitler's theory of absorption,[38] for cosmic-ray energies there is a striking similarity in the dissipation of energy by photons and electrons. This is shown graphically

[37] A. H. Compton and R. J. Stephenson, Phys. Rev. **45**, 448 (1934).
[38] H. Bethe and W. Heitler, Proc. Roy. Soc. London **A146**, 83 (1934).

in Fig. 11, adapted from their paper. We may note that for electrons it is the electron collisions that result in "range" absorption. For energies greater than about 200 mc^2 or 10^8 ev the radiation process is the predominant factor, and the absorption should correspondingly be of the exponential type. This includes all of the important cosmic-ray energy range. Similarly, for energies greater than about 30 mc^2 pair production becomes the predominant method of energy dissipation for photons. It is especially to be noted as shown by the solid line, that while in the low energy range electrons are stopped much more quickly than photons, for energies greater than 1000 mc^2, or 5×10^8 ev, the predicted absorption rate for electrons is but little greater than for photons.

These major results are common also to the extension of Bethe and Heitler's theory proposed by Oppenheimer,[39] and to the alternative theory of Swann.[40] The rate of energy loss by electrons in lead as measured by Anderson has substantiated the predictions up to 800 mc^2, and shows at least no major departures up to 2000 mc^2. The theory is likewise consistent with what little is experimentally known regarding the absorption of high energy photons.

With this theory in mind, the remaining objections[5] to the primary electron hypothesis for cosmic rays are immediately answerable: (3) The photons which occur with energies up to 2.5×10^9 ev, as shown by photographs of cosmic-ray showers, may readily be interpreted as secondaries when we remember that primary electrons are found with energies more than 10 times as great, as proved by equatorial directional experiments. (4) The statement that the hypothesis of primary electrons would leave very few observable electrons at sea level in the intermediate energy range between 3×10^8 and 3×10^9 ev leaves out of account the tertiary electrons excited by the secondary photons, which would be expected to have energies within this range. (5) The claim that photons are 100 times as penetrating as electrons of the same energy is inconsistent with our present knowledge. (6) "Exponential" absorption for rays of cosmic-ray energy is not to be considered a unique characteristic of photons.

(7) The increase in penetrating power with depth at the equator, where the low energy primary electrons are absent, has been considered[5] to favor the primary photon hypothesis. It may be noted that Bethe and Heitler's theory, resulting as it does in a practically uniform absorption coefficient in air or water for all photons of energy greater than 10^7 ev, provides no means whereby *photon* radiation can be hardened as it traverses the atmosphere. Swann has suggested[40] a modification of the theory which would result in increased penetrating power of *electrons* on passing through matter. An alternative interpretation is the assumption that the electrical particles are of two or more types, such as electrons and protons. Protons should excite very little radiation, and should be much more penetrating. They should thus remain after the electrons are absorbed. There are some difficulties with this suggestion, though there are also several lines of supporting evidence. In any case the difficulty of accounting for the hardening of the rays on traversing matter is not removed by substituting photons for electrons as primary rays. On the other hand, direct coinci-

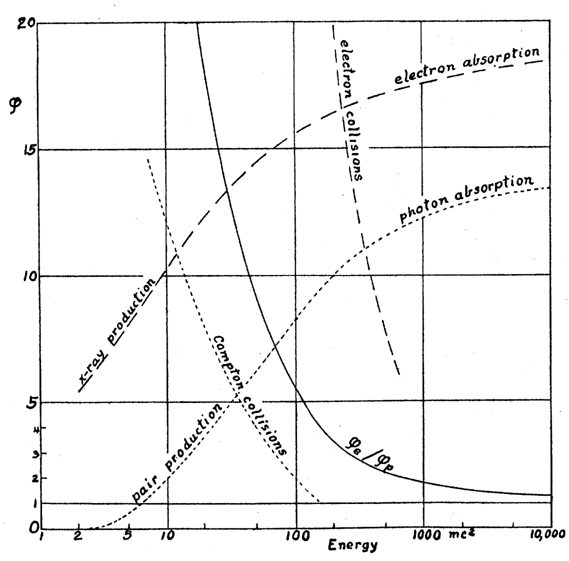


FIG. 11. Effective cross section (units $Z^2r^2/137$) of water molecules for the production of radiative and electron collisions by high energy electrons (broken lines), and pair production and Compton effect collisions by photons (dotted lines). The solid line gives the ratio of the total absorptional cross-sectional areas for electrons and photons (adapted from Bethe and Heitler).

[39] J. R. Oppenheimer, Phys. Rev. **47**, 44 (1935).
[40] W. F. G. Swann, Phys. Rev. **46**, 828 (1934); **47**, 250 (1935).

dence counter experiments by Rossi[28] and others, which record only electrical particles, show a continual hardening as the thickness of the absorption screen is increased to 100 cm. This constitutes direct evidence that electrical rays are hardened by filtering through matter.

(8) The observation by Anderson[41] of nearly equal numbers of positive and negative particles, at least for energies up to 10^9 ev, is taken[5] to imply that the electrons are secondaries resulting from pair production. This is undoubtedly the correct interpretation for most of the lower energy particles. Johnson[31c] has however given apparently conclusive evidence that the so-called "shower producing" cosmic rays are due to primaries consisting of approximately equal numbers of positive and negative rays. This evidence consists in showing that these rays are subject to the latitude effect and are hence electrical, but show very little directional asymmetry and must thus include equal numbers of positive and negative particles. It is thus unsafe to conclude from an equal distribution of positive and negative electrons that they are of local origin.

(9) In earlier discussions[3, 4] the flattening of the altitude *vs.* ionization curve at very high altitudes, as observed by Regener, was taken to indicate the photon character of the primaries, which should not ionize until they had produced secondary electrons, and should thus show feeble ionization near the top of the atmosphere. When, however, the Century of Progress balloon flight, made at a higher magnetic latitude, showed no such flattening, it became clear[1a] that this was a geomagnetic phenomenon, and indicated that the corresponding portion of the radiation is electrical in character.

Summary

These arguments accordingly fail to give any support to the photon hypothesis of the primary cosmic rays. They receive, however, a straightforward interpretation on the hypothesis of electrical primaries if we assume the correctness of the current theories which make photon production the chief mechanism by which an electron loses its energy.

On the other hand, near the top of the atmosphere latitude and directional experiments show that definitely more than 75 percent and probably more than 95 percent of the ionization near the poles is due to charged primaries.

At sea level, the latitude effect establishes the electrical origin of 17 percent of the ionization, and when analyzed in terms of energy distribution indicates a similar origin of a much larger part, very possibly the whole, of the ionization. Directional experiments also show that at least 12 percent of the remainder is electrical. The observed small magnitude of the diurnal changes of cosmic rays caused by the earth's motion with the rotation of the galaxy, seems irreconcilable with more than a few percent of primary photons. Coincidence counter experiments confirm this result, showing that all the coincidence producing rays, within a probable error of about 3 percent, are due to primary electrical particles.

At great depths, the fact that coincidence counting tubes give absorption values in good agreement with those from ionization measurements is evidence that the most penetrating cosmic rays also are electrically charged particles

It is rather surprising to note that there has not appeared positive evidence of a reliable character for any photons whatever among the primary cosmic rays It seems certain that they are not responsible for any of the major features of the rays as we now know them.

In order to describe adequately the properties to the cosmic rays, it seems necessary to assume the presence of both positive and negative electrons among the primaries. There is also some suggestion of the existence of protons. We cannot now discuss these interesting details. It seems however fair to consider the electrically charged nature of the primary cosmic rays as one of their important characteristics established by the last decade of cosmic-ray research.

[41] C. D. Anderson and S. H. Neddermeyer, Proc. Int. Conf. on Physics (London, 1935), Vol. I, p. 171.

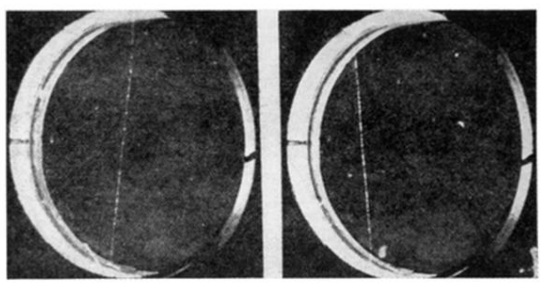
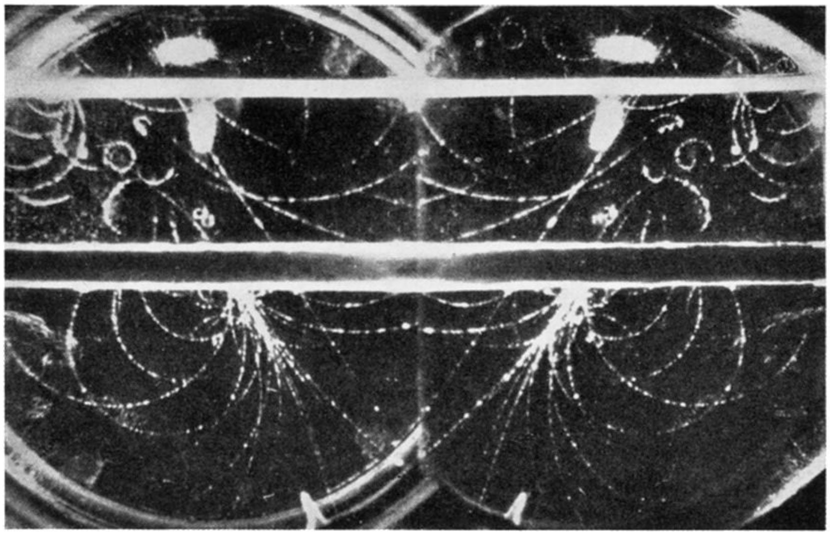
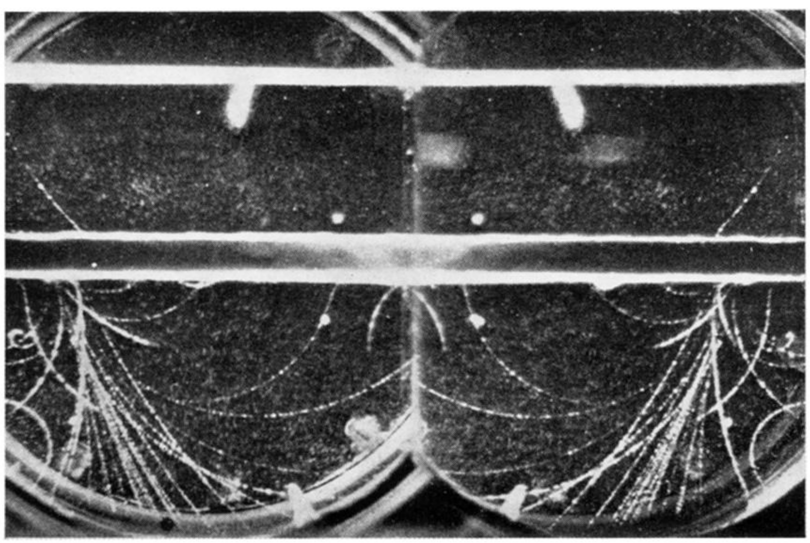


FIG. 6. Trails of two cosmic-ray particles after traversing 40 cm of lead (Street-Woodward-Stevenson).





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