levels.) It remains to consider the various possibilities for V_{0i}.

Electrostatic polarization of the core cannot be responsible for mixing into the ground state excited levels with $L\neq 0$ and $S\neq\frac{1}{2}$, since the electrostatic interaction commutes with the orbital and spin angular momenta separately, and hence will have no matrix elements non-diagonal with respect to L and S. Neither will the ordinary vector couplings, $\mathbf{l}_1\cdot\mathbf{s}_2$, $\mathbf{s}_1\cdot\mathbf{s}_2$, $\mathbf{l}_1\cdot\mathbf{l}_2$. Even the spin-orbit-spin interaction,[4] which in general has mean values non-diagonal in the total spin, does not perturb ^2S states, since the J value for a quartet S level is $\frac{3}{2}$. It follows that although there may be some mixture of excited configurations in the ground state the g_J factor is essentially unperturbed.

If the wave equation for the entire atom, including the nucleus, is used to determine the dependence of the energy E on a weak magnetic field H and dE/dH is then computed there is a small term due to the motion of the nucleus. This term is of the form $(e/2mc)(2m/M)[y_ip_{x_j}+y_jp_{x_i}-x_ip_{y_j}-x_jp_{y_i}]$, and is analogous to the Hughes-Eckart term which describes the specific isotope effect.[5] There will be non-vanishing matrix elements if i refers to the s electron and j to a p shell electron of parallel spin, but since both the s orbit and the closed p shell are spherically symmetric there will be no net contribution to the magnetic moment of the ground state. (The quantity in brackets has so small a mean value, besides having as a coefficient the ratio of the electron mass to that of the nucleus, that the estimated effect on the g factor for a P state of sodium is of the order 10^{-6}.)

Relativistic corrections have already been treated by Margenau.[6] For a $^2S_{\frac{1}{2}}$ level his formula reduces to $g_J=2(1-\frac{1}{3}v^2/c^2)$. This correction term is roughly the same for Na, Rb and Cs, and amounts to about 10^{-5}. This is too small to affect the measurements of Millman and Kusch.[1]

---

[4] E.g. H. A. Bethe, *Handbuch der Physik* Vol. XXIV, 1, 380.

[5] D. S. Hughes and C. Eckart, Phys. Rev. **36**, 69, 694 (1930).

[6] H. Margenau, Phys. Rev. **57**, 383 (1940).

JULY 15, 1941 PHYSICAL REVIEW VOLUME 60

The Thundercloud as a Source of Penetrating Particles

E. C. Halliday
University of the Witwatersrand, Johannesburg, South Africa

(Received April 28, 1941)

The paper describes cloud-chamber experiments designed to test the hypothesis that the electrostatic fields in thunderclouds can produce showers of electrons with energies as great as those found in the penetrating radiation. Sixty-five thunderstorms were observed and five thousand photographs of electron tracks were taken, together with four thousand five hundred control photographs. A statistical examination of the relative number of penetrating electron tracks seen in the two sets of photographs indicates that there is a very strong possibility that penetrating electrons *are* ejected from thunderclouds and reach the earth at considerable distances from the clouds. Evidence is thus obtained that storm clouds act as a source of penetrating electrons, but it is not known whether they are the only source. The experiments indicated that the simple hypothesis, that the penetrating electrons, after their ejection from the storm clouds travel in helical paths about the earth's magnetic field, is untenable.

INTRODUCTION

In 1925 and again in 1929, C. T. R. Wilson suggested that it was possible for thunderclouds, by reason of their very high potentials, to produce a shower of high speed electrons, with energies as high as 5×10^9 electron volts.[1,2] As the polarity of thunderclouds is predominantly positive (the positive charge being above the

---

[1] C. T. R. Wilson, Proc. Camb. Phil. Soc. **22**, 534 (1925).

[2] C. T. R. Wilson, J. Frank. Inst. **208**, 1 (1929).

negative charge), the process envisaged by Wilson involves the projection of the electrons in a more or less upward direction at the instant that the electric moment of the cloud is destroyed by the action of a lightning flash. The electron is accelerated upwards by the field between the positive and negative charges of the cloud, and when it passes above the upper positive charge it enters a reversed field which would retard its speed and reduce its energy. At the instant of the lightning flash, however, the electric moment of the cloud is destroyed and all the electrons which are traveling through the cloud are freed from the action of the reverse field above the cloud, and so escape with their full energy.

TABLE I. *High energy electrons.*

	STORM CONDITIONS	CONTROL CONDITIONS
No. of photographs M	918	928
No. of high energy tracks N	430	395
Probability of capture P	0.468	0.425
$P_s - P_c$	0.043	
Std. dev. for $P_s - P_c$	0.030	
Confidence coefficient	0.8	

In his Franklin Society lecture[2] Wilson suggested that the electrons would then describe helical paths round the lines of force of the earth's magnetic field, subsequently returning to the earth at great distances from the cloud which had produced them. The work which has been carried out during recent years on the production of high energy secondaries by high energy primary radiation indicates that high energy electrons produced by stormclouds may be the parent particles for a number of generations of secondary particles, and that finally there may come to earth, not the original electrons, but the products of this process of secondary production.

This hypothesis has been the subject of three experimental investigations: by Schonland in 1930,[3] by Schonland and Viljoen in 1933,[4] and by Halliday in 1934.[5] This paper describes a fourth set of observations designed to test the hypothesis still further.

The method used was to expand a cloud chamber on a large number of occasions at the same instant as the occurrence of a lightning flash, and also to expand the chamber a further large number of times quite at random. The argument was as follows: if the destruction of the electric moment of the cloud by a lightning flash releases high energy electrons from the cloud, then, when the chamber is expanded at the instant of the flash, the chance that one of these electrons will pass through the chamber and produce an electron track is higher than it would be if the chamber were to be expanded at any other time. Thus, in the expansions made at the instant of a lightning flash, we would expect the number of electron tracks seen in every 100 expansions to be greater than in the case of the expansions made quite at random. If the storm has no action in producing high speed electrons these figures for the two sets of experiments should be the same.

APPARATUS

A simplified type of cloud chamber was constructed, similar to that described by C. T. R. Wilson.[6] The pressure in the chamber was raised to a fixed value above atmospheric pressure, and, when a large valve was opened by means of an electromagnetic trigger, the pressure fell very rapidly to atmospheric. The chamber was connected to a mercury manometer which had movable electric contacts in the open limb connected to a relay. The relay controlled the air pump for the chamber and so the expansion ratio could be set and maintained, by setting the contacts.

In order to check the satisfactory operation of the chamber it was customary, at regular intervals, to make an expansion with a small gamma-ray source near the chamber and see that satisfactory photographs of tracks were obtained.

For synchronizing the expansion of the chamber with the lightning flashes, a three-valve amplifier was connected to a small aerial and tuned to a frequency of 30 kilocycles per sec., as Schonland has shown that this is the frequency emitted by the stepped leader which initiates a "groundflash." The output of the amplifier operated a

---

[3] B. F. J. Schonland, Proc. Roy. Soc. **A130**, 37 (1930).

[4] B. F. J. Schonland and J. P. T. Viljoen, Proc Roy. Soc. **A140**, 314 (1933).

[5] E. C. Halliday, Proc. Camb. Phil. Soc. **30**, 206 (1934).

[6] C. T. R. Wilson, Proc. Roy. Soc. **A142**, 88 (1933).

gas-filled relay and caused the expansion of the cloud chamber. During the first set of observations this amplifier was part of a radio direction finder so that it was possible to record the compass bearing of almost every flash which caused the chamber to expand. During the second set of observations the direction finder was dispensed with, and the cloud chamber was placed between the poles of an electromagnet capable of producing a horizontal field of 1000 gauss fairly uniformly over the whole volume of the chamber. This meant that the stereoscopic camera which was used during the first set of observations had to be discarded, and photographs were taken with a single camera by means of an inclined mirror between the pole face of the magnet and the front of the chamber. The information obtained with the direction finder and with the stereoscopic camera was used for two secondary lines of investigation which are discussed later in the paper.

The Relative Number of Tracks Seen Under Two Conditions of Chamber Operation

During the first set of observations (made during the summer of 1936–7) 24 thunderstorms were studied and 918 photographs of electron tracks were taken. The control observations consisted of 928 expansions made in small groups of 30 to 40 on various occasions between the days on which the storms occurred.

It was not possible to eliminate radioactive contamination from the room in which the cloud chamber was operated, and as a result each photograph taken during an expansion was liable to show electron tracks of relatively low energy, as well as the tracks of penetrating electrons. An energy measurement by means of magnetic bending would have separated the electron tracks of radioactive origin from those of the higher energy penetrating electrons; but no magnetic field was then available, so the tracks were divided into two categories by inspection. Any track which showed any sign of bending was placed in the class of "low energy" and all others were taken to be of "high energy."

The observations are summarized in the case of "high energy" electrons in Table I. Here the first line shows the number of photographs taken under "storm" conditions and under "control" conditions. The second line shows how many "high energy" tracks appeared in these photographs. In the third line, the probability of capture (P) means the average number of tracks seen per photograph, and is therefore the quotient of the first two lines. It will be seen that the probability of capture during storms (P_s) is greater than the probability of capture under control conditions (P_c). The difference between the probabilities is 0.043, and it is necessary to decide whether this difference is significant or merely due to chance.

In an experiment in which M_s photographs are taken under storm conditions, let the number of tracks obtained be N_s. If the experiment were repeated again and again, the same number of photographs M_s being taken every time, the value of N_s would vary about its ultimate mean value $\bar{N}_s$ with a distribution that is almost "normal" and with an ultimate standard deviation $\sqrt{\bar{N}_s}$.

Similarly, if a control experiment with M_c photographs were repeated a large number of times, the value of the number of tracks obtained (N_c) would be distributed almost "normally" about its ultimate mean value $\bar{N}_c$ with an ultimate standard deviation $\sqrt{\bar{N}_c}$.

From this it may be shown that the value of P_s-P_c for successive pairs of experiments will be distributed normally about its ultimate mean value, with an ultimate standard deviation given by

$$\left(\frac{\bar{N}_s}{M_s^2}+\frac{\bar{N}_c}{M_c^2}\right)^{\frac{1}{2}}.$$

This expression, with N_s and N_c used as estimates of $\bar{N}_s$ and $\bar{N}_c$ gives the standard deviation in the fifth line of Table I.

Table II. *Low energy electrons.*

	Storm Conditions	Control Conditions
No. of photographs M	918	928
No. of low energy tracks N	508	527
Probability of capture P	0.554	0.567
P_s-P_c	−0.013	
Std. dev. for P_s-P_c	0.035	
Confidence coefficient	0.3	

TABLE III. *High energy electrons.*

	STORM CONDITIONS	CONTROL CONDITIONS
No. of photographs M	4053	3611
No. of high energy tracks N	722	499
Probability of capture P	0.178	0.138
$P_s - P_c$	0.040	
Std. dev. for $P_s - P_c$	0.009	
Confidence coefficient	0.99	

Considering the hypothesis that the process of synchronizing the expansion of the cloud chamber with a lightning flash does *not* affect the number of tracks observed, we then have a quantity $P_s - P_c$ with an ultimate mean value of zero, observed to be as large as 0.043, when its standard deviation is only 0.030. Tables[7] show that in repeated experiments such a large deviation from zero would occur in only 16 percent of the experiments performed. We can therefore state with a confidence coefficient of 0.84 that the differences between the storm count and the control count *is significant.*

It is of considerable interest to apply the above reasoning to the "low energy" class of electrons which are presumably of local origin so that their frequency of appearance should be the same, no matter at what moment the cloud chamber is operated. The observations are summarized in Table II, where the successive lines have the same meaning as in Table I.

In this case the statistical tables show that with a standard deviation of 0.035, a deviation from zero of 0.013 would occur in 70 percent of a series of such experiments. It is therefore clear that the deviation which was observed is of *no significance*, a result which we expected to find on our hypothesis that the low energy electrons were of local origin. This in itself helps to make the results for the "high energy" electrons more significant than they would perhaps have appeared by themselves.

During the 1938–9 storm season, 41 thunderstorms were observed. At this time the electromagnet was in use so that it was possible to divide the tracks more precisely into two classes (high and low energy). The value 10^6 ev as a dividing line between the two categories was chosen arbitrarily, because it was the highest energy which could be measured with the magnetic field, and because it is just possible to consider 10^6 ev as the lower limit of the penetrating ray spectrum. The results for the "high energy" and the "low energy" electron tracks appear in Tables III and IV, where the significance of the various lines in the tables is as before.

It will be seen that though four times as many photographs were taken as in the 1936–7 storm season, the yield of high energy tracks was only 1.5 times as great. This is probably due to two causes. First, the pole pieces of the electromagnet constituted a fairly thick screen for any particles which entered the chamber either through the front or the back. Thus many particles at the low energy end of the spectrum must have had their energy so reduced that they appeared in the "low energy" class. Second, the chamber in its new set-up between the poles of the magnet, had a slightly smaller effective volume than in the earlier set of observations.

In Table III, it will be seen that the difference $(P_s - P_c)$ is 0.040, a value nearly the same as that obtained in Table I. The standard deviation, however, is much lower, on account of the larger number of photographs taken, and so the reliability of the result is greater. Once again, starting with the hypothesis that the synchronizing of the expansions with lightning flashes does *not* affect the number of tracks observed, we see from statistical tables that a deviation of 0.040 from the expected value zero for the quantity $(P_s - P_c)$ would be observed in only 1 percent of a series of observations. Thus it can be said with a confidence coefficient of 0.99 that the observed deviation *is significant.*

TABLE IV. *Low energy electrons.*

	STORM CONDITIONS	CONTROL CONDITIONS
No. of photographs M	4053	3611
No. of low energy tracks N	2148	1992
Probability of capture P	0.531	0.552
$P_s - P_c$	−0.021	
Std. dev. for $P_s - P_c$	0.017	
Confidence coefficient	0.77	

The values for the "low energy" tracks in Table IV show, as in Table II, a negative value

---

[7] R. A. Fisher, *Statistical Methods for Research Workers* (Oliver and Boyd, Edinburgh, 1938), seventh edition.

for P_s-P_c. According to statistical theory this value (-0.021), would be obtained in about 23 percent of a series of observations.

Here again it is important to notice the tremendous difference between the "high energy" and the "low energy" tracks. The first are very much affected by the process of synchronizing the cloud-chamber expansion with a lightning flash, while the second are only slightly affected by the process, and in the reverse manner.

It will almost certainly be asked, "Was it not possible that the observer, when scrutinizing the photographs and counting the tracks seen, was influenced by a knowledge of what should happen, and when he examined 'storm' photographs counted too many 'high energy' tracks and too few 'low energy' tracks? This would account for the value (P_s-P_c) being positive for the 'high energy' tracks and negative for the 'low energy' tracks." The answer to that is that all the photographs were numbered in code before they were examined at the end of the season, so that the scrutineer did not know the category into which any photograph fell, and thus an unbiased count was obtained.

It is therefore claimed that reliable evidence has been obtained that thunderclouds are instrumental in producing penetrating particles at the surface of the earth, at a considerable distance from the scene of the storm activity.

TWO TESTS OF THE MAGNETIC BENDING HYPOTHESIS

1. Analysis of the compass bearings of lightning flashes which produced penetrating electrons

The work described was designed to test the simple hypothesis of Wilson that the electrons, after leaving the cloud, traveled in helical paths about the direction of the earth's magnetic field. The later discoveries of the production of secondary and tertiary, etc., particles necessitates a more complex hypothesis and it will be seen that the evidence offered here *does* indicate that the helical path is too simple a picture of the manner in which the penetrating particles travel from the cloud to the ground.

TABLE V. *Directional effects for high energy electrons.*

Bearing of Flashes	Number of Photographs Taken	Number of Tracks Observed
NW to SW	273	74
NE to SE	272	72

If particles are ejected from the cloud, they will be traveling in a general upward, though not necessarily vertical, direction. One certain statement can be made, however. If the particles are negative electrons they must return to the earth at some point to the *east* of the cloud. Thus a test of the hypothesis is to compare the number of tracks observed in photographs taken when the flashes were to the *west* of the cloud chamber with the number observed when the flashes were to the *east* of the cloud chamber.

TABLE VI. *Angle of arrival of high energy electrons.*

	Control Observations		Storm Observations	
Angular Interval	No. of Tracks	Mean Angle ×No. of Tracks	No. of Tracks	Mean Angle ×No. of Tracks
90– 80	4	340	3	255
80– 70	13	975	18	1350
70– 60	17	1105	21	1365
60– 50	17	935	13	715
50– 40	16	720	30	1350
40– 30	8	280	21	735
30– 20	10	250	16	400
20– 10	11	165	8	120
10– 0	4	20	11	55
0–(−10)	6	−30	14	−70
−10–(−20)	7	−105	8	−120
−20–(−30)	2	−50	3	−75
Totals	*115*	*4605*	*166*	*6080*
Average angle =		40°		36.6°

The meteorological conditions made it difficult to obtain a great many storms to east and west of the laboratory, for most of the storms started many miles to the south of the city and traveled rapidly to the north, so that they were to east and west for only a short part of their existence.

During 1936–7 a radio direction finder was used to note compass bearings of flashes which produced an expansion of the cloud chamber and the information obtained is shown in Table V. Here only "high energy" tracks are shown.

Here, as in the work done at Cambridge, the total number of tracks is rather too small to warrant the application of statistical theory for the calculation of standard deviations. Thus the result is not conclusive, but the magnetic bending hypothesis is not supported.

2. Study of the directions of arrival of penetrating electrons

A further consideration of the paths of electrons ejected from thunderclouds and spiralling about the direction of the earth's magnetic field shows that the only particles which could reach the ground at a point approximately to the east of the cloud would be those electrons which started their journey in a plane at right angles to the magnetic field, or very nearly in that plane. These particles, when they arrived at the cloud chamber, would still be in that plane, or nearly in it.

Accordingly, during 1936–7, stereoscopic photographs were taken of the electron tracks, and all those "high energy" tracks which could be seen in both photographs were plotted in space. The angle which the track made with the plane at right angles to the earth's magnetic field was measured. When the track showed that the particle had approached the chamber on the *north* side of the plane, the angle was called positive, while a negative sign was given to the angle when the particle had approached from the *south* side of the plane. The tracks were classified in groups, all those which had angles to the plane between ten-degree limits being gathered together, and the results of this process are shown in Table VI.

In the table the observations have been treated as follows: The first column gives the angular intervals into which the tracks were classified. The second column shows the number of tracks which fell in that interval in the case of the control observations, while the third column gives the result of multiplying the number of tracks by the mean angle of the interval. The fourth and fifth columns repeat columns 2 and 3 for the case of the storm observations. At the bottom of each column appears the sum of the figures, and from these is obtained what has been called an average angle, the result of dividing the column 3 sum by the column 2 sum.

It will be seen that the average angle for the storm observations is less than that for the control observations, leading to the suggestion that more of the tracks were close to the plane at right angles to the earth's magnetic field than in the case of the control observations.

It remains to test if this reduction of angle is real and ascribable to any cause other than the variation of two samples from the same population of electron tracks. Standard statistical methods, based on the student distribution were used to evaluate the confidence interval to be associated with the quantity $(\bar{\theta}_s - \bar{\theta}_c)$. For the control sample $\delta = 29°$ and $n = 115$ while, for the storm sample, $\delta = 28°$ and $n = 166$. Using these figures, we have $(\bar{\theta}_s - \bar{\theta}_c) = 3.4° \pm 6.8°$ with a confidence coefficient of 0.95. It will be seen at once that there is no reason to suppose that the two samples labeled "storm" and "control" were from two different populations of electron tracks, as far as direction of arrival is concerned, so that there is no evidence for the simple theory of magnetic deviation of the electrons ejected from storm clouds.

Grateful thanks are due to Professor H. H. Paine, who gave laboratory facilities at the University of the Witwatersrand, to Professor B. J. Schonland and Dr. G. G. Wiles, who supplied most helpful and constructive criticism as the work proceeded, and to Mr. P. C. Roberts who made the cloud chamber and other auxiliary apparatus. The expenses of the work were met by a grant from the Research Grant Board of the Union of South Africa, and from the Joule Fund of the Royal Society, through Professor Schonland.