Cosmic Radiation

M.E Bellerby
### COSMIC RADIATION

#### CONTENTS

<table>
<thead>
<tr>
<th>Page</th>
<th>Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Historical Introduction</td>
</tr>
<tr>
<td>11.</td>
<td>The Absorption Curve</td>
</tr>
<tr>
<td>19.</td>
<td>The Atmospheric Absorption Curve</td>
</tr>
<tr>
<td>28.</td>
<td>Discussion of the Absorption Curve</td>
</tr>
<tr>
<td>37.</td>
<td>Evidence from the Absorption Curve for the presence of Corpuscular Rays</td>
</tr>
<tr>
<td>46</td>
<td>Investigation with Geiger Müller Tube Counters</td>
</tr>
<tr>
<td>55</td>
<td>Störmer's Theory of the Paths of Charged Corpuscles moving in the Earth's Magnetic Field</td>
</tr>
<tr>
<td>69</td>
<td>The Latitude Effect</td>
</tr>
<tr>
<td>77</td>
<td>The Azimuthal Asymmetry</td>
</tr>
<tr>
<td>81</td>
<td>The Transition Effect</td>
</tr>
<tr>
<td>88</td>
<td>Fluctuations in the Intensity of Cosmic Radiation</td>
</tr>
<tr>
<td>97</td>
<td>Wilson Expansion Chamber Photographs</td>
</tr>
<tr>
<td>102</td>
<td>Conclusion</td>
</tr>
</tbody>
</table>
HISTORICAL INTRODUCTION.

In 1902 H.L. Cooke working with Professor Rutherford at the McGill University, Montreal, discovered that the rate of discharge of an electrometer could be very much reduced by surrounding it with screens of various substances (lead, iron, water) (Phys. Rev. 94, p. 183, 1902; Phil. Mag. 6 p. 403, 1903). This indicated the presence of a hitherto undiscovered penetrating radiation in the atmosphere, and it was suggested that the origin of the radiation was to be found in the small quantities of radio-active substances which occur in the earth's crust, and hence also in the walls of buildings, which give rise to ionising radiations. If this were the correct explanation, the intensity of the penetrating radiation would decrease with altitude above the earth's surface. On 11th December 1909, a Swiss physicist, Gockel, took an electroscope up in a balloon from Zürich to a height of 4.5 kilometres, and found that the rate of discharge was not appreciably different from that at the earth's surface. (Phys. Zeitschr. 11, 280, 1910). Later balloon flights of Gockel and of an Austrian physicist, Hess, from Vienna, with improved apparatus, led Hess to state that "eine Strahlung von sehr hoher Durchdringungskraft von oben her in unsere Atmosphäre eindringt, und auch noch in deren untersten
Schichten einen Teil der in geschlossenen Gefässen beobachteten Ionisation hervorruppt. Die Intensität dieser Strahlung scheint zeitlichen Schwankungen unterworfen zu sein, welche bei einstündigen Ableungsintervallen noch erkenbar sind". (Phys. Zeitschr. 12, 998, 1911; 13, 1094, 1912; 14, 610, 1913). Hess goes on to say that as he finds no decrease in the intensity of the radiation at night, it cannot be a radiation proceeding directly from the sun to the earth, and thus the problem of cosmic radiation was first stated.

These earlier investigations of the intensity of the radiation in the earth's atmosphere have been repeated many times, and the conclusions of Hess confirmed. The experimental work has developed along three main lines, as the outcome of employing three different methods for obtaining knowledge of the properties of the radiation. These methods depend respectively upon the use of

a) Ionisation chambers, with which the earlier work was done, and which are still yielding important results;

b) Geiger-Müller tube counters, which were first described by Geiger and Müller in 1923 (Phys. Zeitschr. 29, 839, 1923).

c) Cloud expansion chambers.

A brief account of the main features of the results will now be given.
Ionisation Chambers.

Ionisation chambers have been used by many workers, notably Hofmann, Steinke, Hess, Kolhörster, Millikan, Stenike, Regener, J. Clay and A.H. Compton, to investigate the variation of the intensity with altitude and with depth in water. Regener has shown that the intensity of the radiation in the atmosphere increases to such a value that at a height of 25 kilometres above sea level, 330 ions per cc per second (330 J) are formed in a Chamber containing air at normal pressure, or about 150 times the value at sea level. His measurements in Lake Constance show that the radiation can still be detected at a depth of 230 metres of water; in order to make it possible to measure the very small ionisation current at such depths, the ionisation Chamber was filled with carbon dioxide at 30 atmospheres pressure, which increased the ionisation at the surface to 41.7 J, and the lowest value measured was 0.050 J at 230.3 metres, the "residual" ionisation of the chamber, (the current due to the emission of α particles from its walls) having been subtracted from the reading.

In addition to the application of ionisation Chambers to the study of cosmic radiation in the atmosphere and in deep lakes, they have been used by many German workers to investigate the variations in the intensity of the radiation at a given place. These variations may be due to several causes, but chiefly to
Fig. 6: Druckapparat nach Hertling.
changes of atmospheric pressure and temperature; many long
series of experiments have been carried out to show the correla-
tion between the radiation intensity, and pressure and temperature;
and having corrected as far as possible for these influences, to
show a possible correlation between the intensity (under standard
conditions of temperature and pressure), and either solar or
sidereal time. Such experiments as these require extraordinary
sensitivity of apparatus, as the changes to be detected may be
very small compared with the full intensity of the radiation.
Hoffmann (Gerlands Beiträge zur Geophysik 20, 212, 1928) devised
a method for automatic compensation of the ionisation current by
connecting the electrometer system via a sliding contact to a
rotating rheostat. As the electrometer charged up, its
charge was balanced by that received from the potentiometer
battery, the magnitude of the compensating current depending on
the rate of revolution of the rheostat, which could be adjusted
to suit the intensity of the radiation at sea-level at Königsberg
where the apparatus was first used in 1927, or at an altitude of
2456 metres at Muottas Muragl (Upper Engadine) where it has been
permanently set up (Fig. 1) Only changes in the intensity of
the radiation are recorded by electrometer fibre, and thus the
electrometer can be made very much more sensitive than would be
possible if the fibre alone were measuring the total intensity.
Hoffmann, Stenike, and Schmidt have used ionisation chambers to investigate the so-called "Übergangs-effekt", or the form of the absorption curve at a transition from one element to another; in these experiments the two last-named drew attention to the ionisation "bursts" which occurred from time to time in their apparatus, - sudden increases in the ionisation which could only be explained by the appearance of several millions of ions at once in the chamber. (Zeits. für Phys. 75, 115, 1932).

In 1927 a Dutch physicist, J. Clay, took measurements with an ionisation chamber of the intensity of the radiation on a sea voyage from Java to Holland, and discovered the variation of the intensity with latitude. (Proc. Roy. Acad. Amsterdam 30, 1115, 1927). The extensive investigations of Compton and his collaborators (Phys. Rev. 45, 587, 1933) have confirmed Clay's discovery, and thus given strong support to the hypothesis that the primary radiation coming into the earth's atmosphere is at least in part a charged corpuscular radiation; and not entirely an "ultra-γ radiation", for a dependence of the intensity on geomagnetic latitude is a necessary consequence of the corpuscular hypothesis. The ionisation chambers used on the expeditions organised by Compton were filled with argon at a pressure of 50 atmospheres. It has been shown (J. J. Hopfield, Phys. Rev. 45, 675, 1933) that argon is about twice as sensitive as air for use
Fig 2.
in ionisation chambers for measuring the intensity of γ and
cosmic radiation.

**Geiger-Müller Tube Counters.**

Clay's discovery received little recognition until it was
confirmed by Compton's experiments, but the possibility of a
corpuscular penetrating radiation was first discussed by W. Bothe
and W. Kolhörster in several papers which they published in 1929,
describing results obtained with Geiger Müller tube counters. A
Geiger-Müller tube counter is a cylindrical metal tube, with an
axial insulated wire which is earthed through a very high
resistance, say $5 \times 10^9$ ohms. The tube is filled with dry air
to a pressure of a few centimetres of mercury, and the metal
cylinder raised to a potential of 1500-2000 volts. The field
intensity near the central wire is very great, and any negative
ions formed when an ionising particle enters the tube acquire
sufficient velocity before they reach the wire, to form fresh
ions by collisions. Thus there is a rush of negative ions to the
wire, with the result that it becomes negatively charged, and the
field intensity is considerably reduced, until the ions no longer
produce fresh ions by collision, and the discharge suddenly
breaks off. In this way each ionising particle can be separately
recorded. Fig.2 shows the electrical connections.

In the 1929 experiments, Bothe and Kolhörster used two
Geiger Müller tube counters, placed one above the other, and observed that of the discharges in the two tubes, far more occurred simultaneously than could be accounted for by mere chance coincidence. They showed that these "systematic" coincidences were due to the passage of one and the same corpuscular ray through both tubes, since \( \gamma \) radiation alone, if precautions were taken to shield secondary \( \beta \) particles from the tubes, produced neither discharges nor coincidences. By placing a slab of gold four centimetres thick between the tubes, they showed that the corpuscular rays were roughly as penetrating as the cosmic radiation was known to be at that time. Their experiments were continued and developed by Bruno Rossi, who showed that secondary penetrating corpuscles were produced from a lead block, as a result of the passage of primary corpuscles through it, and later (Zeitschr. für Phys. 32, 161, 1933) that more than half the corpuscular rays have a range greater than a metre of lead. In the same paper Rossi describes how he obtained triple coincidences due to a shower of particles ejected from a lead screen. G.W. Gilbert has recently (P.R.S. 144, 559, 1934) used tube counters to investigate the production of "showers by cosmic radiation at different altitudes (at Cambridge, and on the Jungfraujoch, 3500 m, at Eigergletscher 2300 m, and at Zürich 500 m.) These experiments on showers will be described later.
A further possibility with tube counters is the measurement of the intensity in different directions. Two or more counters with their axes in one plane can be used to measure coincidences due to rays coming in particular directions which lie within angles depending on the geometrical arrangement and the dimensions of the counters. By measuring the rates of linear triple coincidences in different directions, T.H. Johnson has been able to demonstrate the existence of azimuthal asymmetry in the intensity. Like the latitude effect, which has been observed both with tube counters and with ionisation chambers, this is a consequence of the bending of the paths of the primary charged corpuscles in the earth's magnetic field, and the discovery of these two effects leaves no doubt that a part at least of the incoming radiation consists of charged particles, the question at present being how much of the observed ionisation in the atmosphere can be ascribed to them, and how much to the presence of a possible radiation.

Apart from any azimuthal asymmetry of the radiation, one would expect a falling off of the intensity with increasing inclination to the vertical, due to the greater absorption of the oblique rays. It follows that the number of discharges recorded by a single tube-counter will be a function of its orientation. A theory giving the number of discharges or coincidences to be
expected in Geiger-Müller tubes used in different positions (vertical, horizontal, etc.) has been very fully worked out by L. Tuwim (Berliner Berichte 1931, pp. 91, 360, & 630; Journal de Physique et Le Radium p. 614, 1932). The theory is valid only if the intensity is equal in all azimuthal directions, which is certainly not the case at low latitudes, but is so nearly so at moderate latitudes that Kolhörster has been able to verify Tuwim's theory by experiments carried out in Berlin.

Expansion Chambers.

In 1927 Skobelzyn (Zeitschr. füür Phys. 45, 354, 1927) found among the photographs of the tracks of β particles in a Wilson expansion chamber, some paths that were unaffected by a magnetic field of 15,000 gauss, indicating an energy of the order of $10^9$ electron volts. Skobelzyn suggested that these very high energy particles might be a part of the cosmic radiation; since then great contributions to our knowledge of the radiation have been made by workers with expansion chambers. In 1932 an American, Carl D. Anderson, made the important discovery that the curvature of the tracks of the corpuscles was not in one sense only, but that both positive and negative particles occurred, yet the ionisation density along the two kinds of tracks, as far as could be judged, was the same (Science 76, p. 233, 1932). Anderson concluded that the positive tracks were due to particles previously
undiscovered, namely, positive electrons, or particles of
electronic mass but carrying a positive sign. This view is not
universally admitted; E.J. Williams has given reasons in a
letter to Nature (Nature 45, p. 731, 1934) for believing the
positive tracks to be due to protons, and one may then suppose
the existence of negative protons to account for the negative
tracks.

Expansion chamber photographs of cosmic rays are also being
taken by Paul Yumza in Rostock, and by P.M.S. Blackett and
Occhialini in London; the latter have devised a beautiful
experimental method in which an expansion chamber is placed
between two Geiger-Müller tubes; an expansion takes place and
the cloud is photographed by a trigger action, which is released
by the passage of a cosmic ray through both tubes, and hence also
through the expansion chamber. In this way they improved on the
previous tedious methods of taking hundreds of photographs at
random, and have obtained many remarkable pictures, demonstrating
the production of "showers" of particles having their origin in
a common point outside the chamber, and of the presence of
positive and negative particles both in the showers, and as
singly occurring tracks.
The first problems that interested investigators of cosmic radiation were concerned with its absorption in a medium; the atmosphere itself is an absorbing medium, the total depth to sea level being equivalent to $13.6 \times 76$ cms = 10.33 metres of water. The absorption curve can be extended by sinking the measuring apparatus in water, or by surrounding it with metal screens. What is actually measured is the number, J, of ions per cubic centimetre per second produced in the chamber by the radiation, that is, the energy absorbed in the chamber per cc per sec. This is closely concerned with the process of ionisation by the radiation, which up to the present is not fully understood; however, the direct ionising agents are certainly the swift charged particles ejected from atoms as the radiation passes through matter, and the number of these present at a given depth in the medium depends upon the quantity of matter through which the radiation has passed, and upon their range in the medium. For example, if measurements of the ionisation current are taken at increasing depths in the atmosphere, and then continued by placing lead screens round the Chamber, the ionisation current after the introduction of the lead first rises, reaches a maximum, and then falls off again (Transition effect, or "Übergangs effekt"). This is due to the production of secondary particles in the lead,
and Fünfer has shown (Zeitschrift für Physik 83, p. 62, 1933) that more of these are produced in the same equivalent thickness of heavy elements than of light elements. Thus at a transition from one absorber to another, the ratio between the number of secondary ionising particles and the intensity of the primary radiation will be altered, and the curve will not represent the decrease in intensity of the primary radiation. This may account for the shape of the upper part of atmospheric absorption curves, which bend over towards the top, becoming concave downwards.

The ions formed in the chamber near the top of the atmosphere must be due to secondary particles ejected from the wall material of the chamber or formed in the gas of the chamber; lower down in the atmosphere the current has been shown to be largely due to secondary particles formed in the air, which penetrate thin-walled chambers, and contribute to the ionisation. In the case of the curve obtained by A.H. Compton and R.J. Stephenson, the chamber walls were equivalent to six centimetres of lead; experiments of Anderson show that the energy loss in lead by electrons of energy about $10^8$ electron volts, is at least $2 \times 10^7$ e.v. per centimetre, or, that $10^8$ volt electrons would be absorbed completely by 5 cm's lead. Thus the ionisation current in Compton's chamber can only be due to the entry of electrons of energy greater than $10^8$ volts, or to correspondingly
energetic photons, and the curve continues to rise, up to the greatest altitude reached without becoming concave downwards. This was what Compton expected, but it is surprising that the curve obtained with a thin walled electroscope of Bowen & Millikan, taken up on the same ascent into the stratosphere, also continues to rise, and shows no sign of falling off at the top.

Before going on to further discussion of absorption curves, a short account will be given of some of the experimental methods employed in their measurement.

**Millikan's Experiments.**

In 1925, Millikan and Cameron began a series of measurements in snow-fed lakes at high altitudes. The reason for the choice of snow-fed lakes was that they believed the water was less likely to be contaminated by radio-active substances. Experiments were carried out in California and in Bolivia, and were continued in 1923 with improved apparatus. The results of the 1923 experiments will be described. A spherical ionisation chamber was used, (Fig. 3) containing air at 8 atmospheres pressure. The walls were of steel 0.6 mm. thick, and the volume was about 1.5 litres. Inside the chamber was the electroscope, which consisted of two quartz fibres fastened together at each end (fig. 4). When charged the fibres repel each other, until the repulsion is balanced by the tension in the fibres. The distance
between the fibres is a measure of their charge, and was
determined by viewing them with a microscope having a scale in
the eye piece. The microscope is removed when the instrument is
sunk in water, and is replaced when it is drawn up again, after
having been left at a given depth for several hours. Measure-
ments were taken in 1926 with this apparatus in Lake Arrowhead
(5,100 ft. San Bernardino Mountains, California) and in Gem
Lake, 250 miles further south in California, altitude 9000 ft.
All the readings fall on a smooth ionisation depth curve, showing
that the intensity is a function of depth below the top of the
atmosphere. Readings were continued down to 70 metres depth.
Fig. 5 shows the curve obtained (Phys, Rev. 31, 925, 1928).

Regener's Experiments.

Millikan's work was extended in 1928 by Regener, who was
able to show that the intensity of the radiation continued to
be measurable down to a depth of 230 metres of water below the
top of the atmosphere. There were two great improvements in
the experimental method: first, a large ionisation chamber, of
volume 33.5 litres, containing carbon dioxide at 29.4 atmospheres
pressure, was used, and the electroscope was built above it;
second the fibre was photographed automatically at regular
intervals at a given depth, so that several readings were ob-
tained at each depth, and the apparatus had not to be drawn to
the surface to take each one. A diagram of the apparatus is
Fig 6. Regener's Self-recording Electrometer

W = wallasite fibre  C = contact-making clock
G = electrode      E = electric lamp
P = photographic plate
L = lens

Fig 1. Regener's Self-recording Electrometer

Fig 2. Regener's Self-recording Electrometer

Fig 4. Regener's Self-recording Electrometer
given in Fig. 6. The electrometer was of the single thread type, the fibre being of wollastonite, about 8 centimetres long, between 2 and 3 μ thick. The lower end was attached to a quartz bow, by moving which the sensitivity of the fibre could be varied. An electrode placed opposite the fibre ensured that it moved in one plane, and also increased the range over which the calibration curve was a straight line. During the measurement, the fibre was illuminated every hour, at a given depth, by means of an electric lamp in series with a contact-making clock, and an image of the fibre was formed on a fixed photographic plate by means of an astigmatic lens system. Fig. 7 shows the photographs of the positions of the fibre at two different depths in water; the distances between successive positions of the fibre were determined as accurately as possible with a travelling microscope. Regener claims that for a range of potential of from 300 - 600 volts the voltage could be estimated accurately to within 0.02 volt. Measurements were taken down to a depth of 230.8 metres, when the total ionisation current was only slightly greater than that due to the "residual ionisation" in the chamber (ions formed by particles shot out from the walls of the chamber). In 1929 a large double walled tank was built, and the outer compartment filled with water from the surface of the lake; the ionisation chamber and electrometer
Diagram of Apparatus used by Regener in Lake Constance
A - Central Chamber
B - Water compartment
C - Air floats
F - Ionisation Chamber

Water Absorption Curve of Regener and Kramer

Fig 9

Equivalent depth below top of atmosphere in metres water

Intensity in ionisation per cm per sec.
were lowered into the central compartment (Fig. 8), being thus protected from radiations due to a possible radio-activity of the deep water or of the floor of the lake. No difference was found between measurements taken with and without the tank. Since the photographs taken near the surface of Lake Constance were not very clear, because of the movement of the water, the measurements were completed by W. Kramer (Zeitschrift für Physik 65, 411, 1933), on the ice of an Alpine lake near Immenstadt in Allgäu, Bavaria. The same ionisation chamber and electrometer were used as for Regener's measurements, and the apparatus was lowered through a hole in the ice to a depth of 20 metres. Fig. 9 shows the water absorption curve obtained by Regener and Kramer.

Absorption Curve of J.M. Benade.

J.M. Benade has published an account of measurements taken in Lake Konsar Nag, Kashmir, 11,600 ft. above sea level. (Phys. Rev. 42, p. 293, 1932). The electrometer consisted of two short parallel phosphor bronze strips, attached at one end only. Their divergence was recorded photographically every eight minutes. The ionisation chamber was at one end of a steel cylinder, with walls 0.8 mm thick, containing air at 11.94 atmospheres pressure. Measurements were taken down to a total depth of 93 metres, and they agree closely with Regener's from 60 to 93 m. depth.
Water Absorption Curves of J. Clay

- Regener's measured values
- Regener's adopted values (after subtracting the residual ionisation)

Gulf of Aden 15° N
Red Sea 18° N

Fig 10

Curves calculated by W. H. Swann

- Curve DEF = ionisation due to showers
- AEB = ionisation due to primary rays no longer producing showers
- DEF = sum of DEF and AEB

Fig 11
Absorption Curve of J. Clay.

An important discovery was made in 1933 by J. Clay, which has not yet been verified by any other experimenter. Clay took measurements in the Red Sea, 15° N, and in the Gulf of Aden, 15° N, and the curves obtained are shown in fig. 10. It is seen that between 200 and 250 metres depth the intensity rises slightly, and at 250 m. falls off suddenly, becoming zero at 270 m. Both curves agree in showing this quite new feature. Clay suggests that the slight increase is due to an increase in the specific ionisation of the penetrating component of the cosmic radiation as it approaches the end of its range, which accounts also for the subsequent rapid falling off. This view is taken by W.F.C. Swann (Phys. Rev. 46, p. 432, 1934), who believes that the primary radiation during the greater part of its range produces showers, which cause the ionisation in the chamber; near the end of the range the primary corpuscles have insufficient energy to produce showers, and ionise then by collisions with extra-nuclear electrons. The ionisation current is therefore a sum of two contributions, that of the showers, and that of the primary rays which are sufficiently oblique to be near the end of their range. From Clay's curve it seems that the range over which the primaries can produce showers is 250 metres, and Fig. 11 shows curves calculated by Swann, giving the
effect of the showers only, and the effect of the end-of-the-range ionisation, and the total effect due to both, which is very like the experimental curve of Clay. This seems a very likely explanation, but Clay's measurements must be confirmed before further attention can be drawn to this point.
Regener's Measurements in the Stratosphere.

Since the intensity to be measured in the upper atmosphere is much greater than at sea level, the electrometer, which was built on the same principle as the one used in Lake Constance, was placed within a spherical ionisation chamber of 2.1 litres capacity, with 0.5 mm. brass walls, filled with air at a few atmospheres pressure. A very successful attempt was made to keep the temperature of the instrument as constant as possible, by constructing a light framework round it, the lower half of which is covered with aluminium foil, and the upper half with cellophane. So effective was the absorption of heat rays by the cellophane that in the first form of the apparatus (Fig. 12) the temperature rose to 55°C at a height of 20 kilometres (where the outside temperature would be near to -100°C) and a different form had to be employed (Fig. 14 shows this later form of apparatus just about to be released for the ascent on 3rd January 1933).

The ionisation chamber containing the electrometer, with the devices for automatic recording of temperature, pressure and position of fibre, is in the inner "stream-lined" case, the lower half of which is covered with aluminium foil, and the upper half with cellophane; the outer case, also "stream-lined" and covered with cellophane but open at the top and bottom, served to
steady the whole apparatus on its journey and to protect the inner part on landing. Two balloons, filled with hydrogen, were used for each ascent, one of which bursts before the other, so that the second brings the apparatus safely to the ground. Below the two balloons in fig. \( / \) is a wooden hoop to which is fixed a hemispherical piece of thin silk with a hole in the middle; this acted as a brake in the ascent. The fibre is photographed every four minutes, instead of every hour, and an automatic record of temperature and pressure is also obtained on the photographic plate by means of an aneroid barometer A and a bimetal strip B (Fig. \( / \) ) both of which carried light rods which moved up and down in front of the fibre, tracing two lines across the photograph, which record the pressure and temperature respectively.

Fig. \( / \) shows the record of the flight on 12th August, 1932.

A narrow scale is also photographed at the same time across the centre of the field of view, between the records of pressure and temperature; on the scale are subsequently written the corresponding heights, determined from the readings of two theodolites at two fixed points on the earth. The temperature record shows that between 10 and 25 km the temperature was not very different from that at ground level.

The four last successful flights made by Regener gave the curves shown in Fig. \( / \) . The accompanying table shows the lowest air pressures reached on the flight, and the air pressure
Regener's Stratosphere
Absorption Curves.

Fig 17
in the chamber.

<table>
<thead>
<tr>
<th>Date</th>
<th>Lowest air pressure in mm.</th>
<th>Air pressure in chamber at 0°C</th>
<th>No. of electrometer</th>
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<td>22</td>
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<td>3.1.33.</td>
<td>34</td>
<td>4.45</td>
<td>5</td>
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<tr>
<td>9.3.33.</td>
<td>17.6</td>
<td>3.28</td>
<td>4</td>
</tr>
<tr>
<td>23.3.33.</td>
<td>32</td>
<td>5.33</td>
<td>4</td>
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Table 1

Fig. 17 shows that the intensity on the last flight rose to a much higher value than on the other three occasions - 15% more at 30 mm. air pressure. The explanation offered by Regener is based on a report (from Prof. W. Brunner, Zürich) that on 28th March at midnight, and for a few hours in the early morning of 29th March, a group of sun spots crossed the central meridian of the sun, which was remarkable since the time of year is a time of minimum sun-spot activity. On the other three days no noticeable spots in the central part of the orb were observed. Regener makes the following remarks (Physikalische Zeitschrift 54, 820, 1933) about the agreement between the four curves: - 'Wenn man den Verlauf der Intensität der Ultrastrahlung (in J bei 0° und 760 mm. ausgedrückt) bei den vier Aufstiegen untereinander vergleichen will, so ist zu bemerken, dass die oberhalb 170 mm. Luftdruck auftretenden Differenzen kaum real sein dürften. Man
Absorption Curves in the Upper Atmosphere.
befindet sich dort in dem Übergangsgebiet von der Troposphäre in die Stratosphäre, womit allerhand Störungen (Temperatursprüinge, Inversionsschichten, Übergang in das Wolkenlose Gebiet) verbunden sind. Die Messgenauigkeit wird dadurch stark herabgedrückt.

Besonders wert ist aber die gute Übereinstimmung aller vier Kurven in etwas größeren Höhen, etwa zwischen 170 und 120 mm. Luftdruck. Besonders auffallend ist aber weiter die Tatsache dass in noch größeren Höhen, bei Drucken unterhalb 100 mm Hg. drei Aufstiege gut Übereinstimmen, dass dagegen der vierte Aufstieg am 29 März um 80 Stärker von den übrigen abweicht zu je größeren Höhen nun kommt. Es fällt schwer diesen Unterschied auf Versuchsfehler zu schieben". On this particular flight the temperature only varied between 6° and 11°C, and a record was obtained both on the ascent and on the descent of the apparatus, not, as in Fig. 16 on the ascent only.

Fig. 18 is taken from Regener’s paper (Physikalische Zeitschrift 34, 306, 1933) and shows his own curve, together with one at lower altitudes obtained by Kolhörster, and Piccard and Cecyna 1932 curve. There is agreement as to the general shape of the curves; their most noteworthy feature is that, instead of rising more and more steeply towards the top of the atmosphere they actually become concave downwards. This property is common to all the Stratosphere curves taken with thin walled
Millikan's high altitude measurements at different latitudes

**Fig. 19**

Aeroplane measurements with and without a lead shield

**Fig. 20**

Aeroplane flights
March Field Calif. 40°N
Upper curve - no shield
Lower curve - shielded by 12cm lead.
chambers, except one, the curve obtained at latitude $52^\circ$ N by Fordney and Settle, with one of Millikan's instruments.

Atmospheric Absorption Curves of Bowen, Millikan and Keber.
(Phys. Rev. 43, 795, 1933; 46 1934).

High altitude measurements at different latitudes of the intensity of cosmic radiation have been organized by Bowen, Millikan and Keber. In 1931 and 1932 five aeroplane flights were carried out, at Cormorant Lake, Manitoba, $63^\circ$ N, Spokane $54^\circ$ N, March Field, California $41^\circ$ N, Panama $20^\circ$ N, and Peru $4^\circ$ S. Photographic records of the position of the electrometer fibre were obtained. Fig. 19 shows the results of the flights. The main interest of the curves lies in the fact that they show an increasing intensity with latitude at high altitudes, even where this is not detectable at sea level; this is discussed in the section on the latitude effect. In addition to the flight at March Field mentioned above, during which measurements were taken with a thin-walled ionisation chamber, similar observations were taken there with the electroscope surrounded by a screen of lead 10 centimetres thick. Fig. 26 shows the two curves obtained.

Anderson has made direct measurements of the energy loss in lead, and shown that for electrons of energy about $10^8$ volts, the loss per centimetre is at least $2 \times 10^7$ electron volts, thus the electrons which succeed in penetrating the lead wall must have at
Stratosphere Observations of Different Investigators

Fig. 21
least \(2 \times 10^8\) e.v. energy. The great difference between the ordinates of the two curves shows that about two thirds, or even more, of the ionisation measured in a thin walled chamber at a depth in the atmosphere of 3 m. water, is due to secondary rays produced in the atmosphere, and that therefore one would expect the curve to become concave downwards at higher altitudes, only reached by balloon flights. A curve taken by Millikan and Bowen using pilot balloons, which rose to a height of one metre of water below the top of the atmosphere, shows this downward concavity in the last metre, yet another, obtained by Fordney and Settle during their stratosphere flight on November 20th, 1933, shows a continuous rise to a depth of rather less than one metre of water. Fig. 24 shows the curves of Regener, Bowen, and Millikan, Piccard, and Fordney and Settle. The latter was taken at the highest latitude 52°N; no shield was used, yet the intensity shows no sign of falling off up to the greatest height reached. The reason for this may be that lower energy electrons, unable to reach the earth at lower latitudes because of the magnetic field, are being admitted here. The lowest energy (in special units) is given by the equation (see later)

\[ l = \frac{-2}{X \cos \theta} + \frac{\cos \beta \theta}{X} \]

which leads to a value of about \(2 \times 10^9\) electron volts. Electrons of this energy can only penetrate to about one third of the
Atmospheric Absorption Curves

R. Reeser 12. 8. 1952 latitude 50° N
P.C. Piccard and 19. 8. 1952 . 46° N
Cosyns
C.S. Compton and 20. 11. 1923 . 52° N
Stevenson

Figure 22.
depth of the atmosphere and therefore, only make their presence felt at depths less than 3 metres water. This is clearly shown in the figure. However, it seems doubtful whether the difference in shape between the Fordney Settle curve, and those for example of Regener, can be entirely ascribed to a latitude effect, for the two flights took place at latitudes not five degrees apart. It may be that in this case, as also in one curve of Regener which rose more steeply than the others, some other factor is causing an increased ionisation in the stratosphere, or it may be that the bending over is caused by some defect in the measurement of intense radiation.

**Compton's Absorption Curve.**

Settle and Fordney also carried one of Compton's ionisation chambers on this stratosphere flight (20th November 1933). It had walls equivalent in thickness to 6 cms. lead, and was filled with argon at 2.4 atmospheres pressure. The six cms Pb prevent the entry of electrons of lower energy than $10^8$ electron volts; the curve continues to rise without showing any tendency to approach a maximum value. If the logarithm of the intensity is plotted against the atmospheric pressure, a "hump" is evident between 20 and 30 cms mercury pressure. Fig. 22 shows Compton's curve and those of Regener, and Picard and Cosyns. The hump is evident in all the logarithmic curves. Compton draws attention
to this and gives reasons for believing that such a hump could only be caused by particles with a definite range in matter, not by photons. This will be discussed later.

The Piccard and Coysne Flight (18th August 1932).

Two ionisation chambers were carried, one containing air at normal pressure, the other carbon dioxide at ten atmospheres. The readings of both lay on one curve which is shown in Fig. Regener's Curve obtained with an open Ionisation Chamber.

In addition to the curves measured with closed ionisation chambers, containing gas at a fixed pressure, Regener has used an open chamber, in which the pressure is always that of the atmosphere outside. The open chamber possesses distinct experimental advantages:

1. The current measured only alters in the ratio 1 to 5, whereas in a closed chamber there is a 150-fold increase.

2. The intense ionisation produced high in the atmosphere in vessels containing gas at a high pressure may mean that relatively a fewer ions reach the electrodes, but this will be avoided by using an open chamber.

3. The curve obtained lends itself to analysis by a method described by Regener and E. Lenz. This will be described later.

The chamber had to be much bigger, in order to measure an ionisation current at low pressures; it was 105 litres in
Fig 23

Intensity of Cosmic Radiation in the Upper Atmosphere
Open Emission Chamber used 30 Aug 1928

Long cm$^2$ Sec$^{-1}$ (open chamber)

Pressure mm Hg. mercury
capacity with aluminium walls 0.3 mm thick. Fig. 23 shows the curve obtained on 30th August 1933, in which there is a maximum ionisation at about 125 mm mercury pressure, and two other slight "humps" are evident.

Cosmic Radiation observed in mines.
Both W. Kolhorster and A. Corlin have found extremely penetrating components of the cosmic radiation; the former working in the Stassfurt salt mine finds that the rays penetrate to a depth corresponding to 600 m. water (Nature 133, p.418, 1934), and the latter, working in an iron ore mine near Kiruna, N. Sweden, finds that they can still be recorded at a depth of 100 m. iron ore, equivalent to 800 m. water.
DISCUSSION OF THE ABSORPTION CURVE.

The Evidence for Ultra $\gamma$ rays of definite absorption coefficients.

Before the corpuscular nature of at least part of the incoming radiation was suspected, Millikan and Regener had attempted to analyse their curves, that is, assuming that they were dealing with an "ultra-$\gamma$-radiation", coming into the earth's atmosphere with equal intensity in all directions, they have tried to show that it consists of a mixture of a few components of definite absorption coefficients.

Consider first radiation of one hardness travelling through a medium in one direction only; the absorption coefficient is defined as follows

$$\frac{d\bar{I}}{dz} = -\mu\bar{I}$$  \hspace{1cm} (1)

where $\bar{I}$ is the rate of flow of energy per square centimetre at a dept $z$, and $d\bar{I}$ is the change in $\bar{I}$ over the depth $dz$. This involves the assumption that the chance of a collision in $dz$ depends only on the number of quanta present, and on $dz$; and that at a collision, the quantum transfers a large part of its energy to the ejected electrons, in the case of nuclear absorption, or to the recoil electron, in the case of absorption by Compton collisions with extra-nuclear electrons.

Equation (1) leads to the exponential expression

$$\bar{I} = I_0 e^{-\mu z}$$  \hspace{1cm} (2)
where $I_0$ is the value of $I$ at $z = 0$. Although $I$ has been defined as the rate of flow of energy per square centimetre, equation (2) will also represent the ionisation-depth curve, because the ionisation at a depth $z$ must be proportioned to the energy flow there.

Since it is known that cosmic radiation enters the earth's atmosphere with equal intensity in all directions, equation (2) has to be extended to apply to this case. Now an ionisation chamber measures the energy absorbed in it due to the production of ions; it does not measure the rate of flow of energy per square centimetre, and therefore the shape of the ionisation depth curve will depend to some extent on the shape of the ionisation chamber. However, an expression can be deduced for the case of monochromatic rays entering a medium with equal intensity in all directions, and measured at a given depth in the medium with a spherical ionisation chamber. At the surface of the medium the rate of flow of energy in directions lying within the limits of a small solid angle $d\Omega$, per square centimetre perpendicular to these directions, will be proportional to $d\Omega$, and therefore the ionisation due to these rays may be written $K d\Omega$. At a depth $z$ in the medium, rays coming in directions inclined at $\theta$ to the vertical, have travelled a distance $z \sec \theta$ in the medium (see Fig. 24) and their intensity will be reduced by the
factor \( e^{-\mu z \sec \theta} \), where \( \mu \) is their absorption coefficient. Suppose a spherical ionisation chamber, of diametral section \( A \) square centimetres, is situated at the depth \( z \), then the ionisation per second due to rays in directions lying within \( d\delta \) is

\[
A d\delta e^{-\mu z \sec \theta}
\]

\( d\delta \) may be written \( \sin \theta d\theta d\phi \), where \( \phi \) is the azimuthal angle, and to find the total ionisation we have to integrate (3) over values of \( \theta \) from 0 to \( \frac{\pi}{2} \), and \( \phi \) from 0 to \( 2\pi \)

Thus

\[
I = A k \int_{\phi=0}^{\phi=2\pi} \int_{\theta=0}^{\theta=\frac{\pi}{2}} e^{-\mu z \sec \theta} \sin \theta \; d\theta \; d\phi
\]

This can be written, by substituting \( x \) for \( \sec \theta \), and \( I_o \) for \( 2\pi k \)

\[
I = I_o \int_{x=1}^{\infty} \frac{e^{-\mu z x}}{x^2} \; dx
\]

This integral is usually represented by the letter \( \phi \); its value will depend only on \( \mu z \), and we may write

\[
I = I_o \phi (\mu z)
\]

The numerical values for \( \phi (\mu z) \) are given in a paper by E. Gold (Z. R. S. 62, p. 62, 1933) or in the appendix of "Radioaktivität", St. Meyer & Schweidler, Leipzig.

Analysis of the experimental absorption curve on the basis
of the $\phi(uz)$ absorption function at once showed that it did not consist of a monochromatic radiation; no single value of $\mu$ used in the expression served to reproduce the measurements. However, by taking components of three or four different absorption coefficients, with different values in each case for $I_0$, a curve can be built up which is fairly close to the experimental curve. Bowen, Millikan and Neher have been able to do this for values of $z$ from 4.5 metres water below the top of the atmosphere, i.e. from the highest points of their aeroplane flights, down to $z = 240$ metres, but it is not possible to obtain a unique solution, as is evident by comparing Tables I, II and III published by them. In one respect the solutions all agree, namely, that a very large part of the ionisation in the atmosphere is due to a soft component of absorption coefficient about 0.5 per metre of water.

Regener, with the help of W. Kramer and E. Lenz, has carried out an analysis of his curve by two quite different methods. The first is based on an absorption function proposed by H. Kulenkampff and applied by W. Kramer to radiation coming with equal intensity in all directions. Kulenkampff supposes that the ionisation in the case of hard $\gamma$ rays is brought about by recoil electrons resulting from nuclear collisions. He considers the possibility that the scattered radiation, which is known to
be scattered forward in directions very nearly that of the primary ray, may itself later produce another recoil electron. He thus builds up a curve consisting of the decreasing primary ionisation, together with the increasing and subsequently decreasing ionization due to scattered radiation. The intensity at a given depth of the once, twice, three times..... etc. scattered radiation is calculated in much the same way as one calculates the number of atoms of a decay product of a radioactive substance at a given time.

W. Kramer has applied the Kulenkampff absorption function to the case of radiation entering a medium with equal intensity in all directions, and with the aid of the final Kulenkampff-Kramer function has analysed Regener's water absorption curve. He finds that it can be built up of four different components, shown in the following table:

<table>
<thead>
<tr>
<th>Absorption Coefficient per metre water</th>
<th>( I_0 ) Ions per cc per sec formed in air at normal pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0209</td>
<td>0.16</td>
</tr>
<tr>
<td>0.075</td>
<td>1.2</td>
</tr>
<tr>
<td>0.16</td>
<td>1.6</td>
</tr>
<tr>
<td>0.52</td>
<td>34</td>
</tr>
</tbody>
</table>
It is seen at once that the absorption coefficients are similar to those obtained by Millikan, especially that again most of the ionisation in the upper atmosphere is caused by a soft component of absorption coefficient about 0.5 per metre. Kramer's method of analysis is to assume that at the greatest depth only one component is still unabsorbed. By taking two values of the ionisation at the tail of the curve, and subtracting from them the "residual ionisation" of the chamber (due to $\alpha$ particles shot out from the walls) he finds what value of $\mu$ in the Kalenramoff-Kramer function will give a curve going through the two points. The ionisation due to this component is computed for all depths, subtracted from the measured curve, and the process started again to find the second component. The chief objection to the method lies in its dependence on the value of the residual ionisation, which according to Kramer was greater than the ionisation due to cosmic rays, for the last hundred metres.

An entirely different method of analysis has been carried out by E. Lenz. Briefly, his argument is as follows: The intensity $I$ of a parallel beam of radiation may be written

$$I = I_0 e^{-\mu (H - H')}$$

where $H'$ is the altitude, measured in kilometres of normal air, and $H$ the corresponding height of the whole atmosphere ($= 8$ kms). Using the fact that the density decreases exponen-
Fig 25

Regener's Stratosphere measurements and Lenz' "deformed" curve

Pressure mms mercury

Deformed Intensity, p.1.
Lns. cm-2 see-1 atm-1
itially with the true altitude $h$

$$\rho = \rho_0 e^{-\frac{k}{H}}$$

it follows at once that $I$ may be expressed in terms of the true altitude

$$I = I_0 e^{-\mu H e^{-\frac{k}{H}}}$$

If the number of ions $q dh$ produced in the distance $-dh$ is proportional to the decrease in intensity over $dh$, we may write

$$-q dh = -c d I$$

$$q = c \frac{d I}{d h}$$

whence

$$q = c I \mu e^{-\frac{h}{H}}$$

It can be shown by differentiating with respect to $h$, that $q$ has a maximum value at a value of $h$ given by

$$\mu = \frac{1}{d} e^{-\frac{h_{\text{max}}}{d}}$$

In order to plot the $q$ curve, it is only necessary to multiply the measured ionisation by the factor $e^{-\frac{h}{H}}$, or more simply by the pressure at height $h$. Fig. 25 shows the deformed curves obtained by Lenz, using the Regener-Kolhörster atmospheric curve. Two distinct "humps" appear, one at an altitude of 13 km and the other at 8 km. If the absorption function for the radiation is
--- Balloon flight with open chamber.

--- Ionisation reduced to normal pressure

--- Average of curves obtained with closed chambers.

--- Ionisation reduced to outside pressure

Fig 26
not the simple exponential, but the Kulenkampff-Kramer function
then the expression for \( \mu \) becomes:

\[
\mu = \frac{1}{0.074} e^{-\frac{h_{\text{max}}}{d}}
\]

Using this expression Lens finds that the absorption coefficients
are as follows:

\[
\begin{align*}
\mu &= 0.96 \text{ per metre water} \quad \text{atmospheric curve} \\
\mu &= 0.46 \quad \text{water curve.}
\end{align*}
\]

These last two are very near to the values found by Kramer in
analysing the water curve. A "deformed" curve may be obtained
experimentally by taking the measurements with an open ionisation
chamber. Fig. 26 shows how closely the measured curve and the
calculated curve agree.

The expression for \( \mu \) if the absorption function is the
\( \phi (\mu) \) law is

\[
\mu = \frac{1}{1.04} e^{-\frac{h_{\text{max}}}{d}}
\]

and the absorption coefficients turn out to be

\[
\begin{align*}
\mu &= 0.49 \text{ per metre water.} \\
\mu &= 0.19 \quad \text{water curve.}
\end{align*}
\]
These are to be compared with a set of Millikan's values

\[
\begin{align*}
\mu &= 0.55 \text{ per metre water} \\
\mu &= 0.12 \text{ " " } \\
\mu &= 0.05 \text{ " " } \\
\mu &= 0.0075 \text{ " " }
\end{align*}
\]

The agreement between the results of the two different analyses, carried out by quite different methods, of different absorption curves, is remarkable. One would not expect Kramer's results, based on a different absorption function, to agree so closely, and in criticism of the absorption process suggested by Kulenkampff and used by Kramer, it may be said that there is no evidence for it from cloud chamber photographs, that it takes no account of shower production, or of nuclear absorption of the rays. It is founded on more assumptions than the \( \beta(\mu z) \) law; in deducing the latter one has to assume that the number of ionising particles formed in a distance \( dz \) in a medium is proportional to \( dz \) and to the intensity of the primary beam, a not unreasonable assumption, which might hold even if the chief mechanism of absorption is the production of showers. It demands that each quantum of the incoming radiation shall lose most of its energy in one encounter, perhaps with a nucleus and it would cease to apply if the energy were lost by a succession of small transfers, as in the case of uniformly ionising particles with a definite range in matter.
Evidence from the Absorption Curve for the Presence of Corpuscular Rays.

Compton has recently published a paper drawing attention to another feature shown by some of the atmospheric absorption curves. Turning back again to fig. 22 showing the logarithmic absorption curves of Compton and Stevenson, Regener and Kolhörster, and Piccard and Cosyns, one notices at once a hump at a pressure of about 50 cms of mercury. It occurs in Compton's curve at a slightly lower pressure than in those of Regener and Piccard, which can readily be explained by the much thicker walls of Compton's ionisation chamber. Since it is evident in three quite independent experimental curves, it seems that it must be caused by some inherent feature of the radiation itself, and not be a result incidental to the experimental conditions. Compton claims that it constitutes a criterion for the corpuscular nature of the radiation, but his argument is based on the assumption that the corpuscular rays have a definite range in matter, and ionise uniformly throughout that range. Let us find the absorption function for such rays, designated by Compton "r-particles". The intensity $I_r$ at a depth $z$ due to a parallel beam may be written

$$I_r = \frac{I_0}{r} \text{ for } z < r$$

$$I_r = 0 \text{ for } z < r$$
Fig 27

A sq. cms.
where \( r \) is the range of the particles, and \( I_0 \) the energy passing per second through a square centimetre perpendicular to the direction of the beam, at the upper limit of the absorbing medium. Now consider the case of \( r \)-particles entering a medium with equal intensity in all directions. At the upper surface of the medium, the number of rays travelling in directions lying within the limits of a small angle \( d\theta \), and passing per second through a square centimetre perpendicular to these directions is proportional to \( d\theta \), and the ionisation due to them may be written \( k d\theta \).

At a depth \( z \), particles coming in the direction \( \theta \) to the vertical have travelled a distance \( z \sec \theta \) (Fig. 17) and only those will contribute to the ionisation for which

\[
0 < \cos^{-1} \frac{z}{r} \quad \text{(arc cos} \frac{z}{r})
\]

For these values of \( \theta \), the rate of ionisation, due to rays travelling in directions \( d\theta \) through an area \( A \) perpendicular to these directions will be \( A k d\theta \), because an \( r \)-particle ionises uniformly throughout its range. Suppose \( A \) is the area of a diametral section of a spherical ionisation chamber, then \( A k d\theta \) represents the ionisation due to the bundle of rays falling within \( d\theta \). The total ionisation \( I_x \) in the chamber is therefore

\[
I_x = \int A k \ d\theta
\]

\[
\beta = 2\Pi \quad \theta = \cos^{-1} \frac{z}{r}
\]

\[
= \int_{\theta = \pi}^{\theta = \pi} \int_{\phi = 0}^{\phi = \pi} \sin \theta \ d\theta \ d\phi
\]
Calculated ionisation

$I_r$ by $r$-particles, of range 60 cms mercury

$I_p$ by photons, of absorption coefficient 0.03 per cm

![Graph showing intensity vs depth in atmosphere](image-url)

Fig. 28

Log $I_r$ and Log $I_p$

Fig. 29

Depth in atmosphere, in cms mercury
where $\phi$ is the azimuthal angle, and $A$ may be brought outside the integration symbol since it is the same for all directions. After integration we have

$$I_r = 2\pi A k \frac{E-E_r}{r}$$

Suppose the value of $I_r$ when $z = 0$ is $I_o$, then

$$I_o = 2\pi A k$$

(which also follows from the definition of $k$) and we may write

$$I_r = I_o \frac{E-E_r}{r}$$

This is to be compared with the corresponding expression for photons; If $I_p$ represents the intensity at a depth $z$ of a photon radiation entering a medium with equal intensity in all directions, then

$$I_p = I_o \phi(\mu z)$$

Fig. 28 shows the graphs of the two expressions $I_r$ and $I_p$, and Fig. 29 their logarithmic curves. The rate of decrease with depth in the medium in the case of an $r$-particle is linear, and the logarithmic curve is concave downwards. If $r$ particles of a few definite ranges are present, the ionisation-depth curve will show discontinuities, wherever particles of a particular range come to the end of their range. If there is a continuous distribution of ranges, suppose $dI_r$ is the ionisation at a given
depth $z$ due to particles of range between $r$ and $r+dr$, where $r \leq z$. Let $I_0(r)$ represent the ionisation due to particles of this range at the surface of the medium. Then

$$dI_r = I_0(r) \frac{r-z}{r} dr$$

The total ionisation at depth $z$ will be obtained by adding the effects of all particles of range $r \leq z$.

$$I_r = \int_{r=z}^{r=\infty} I_0(r) \frac{r-z}{r} dr$$

The integral will be a function of $z$ which will not be linear; it will depend on $I_0(r)$, that is, on the ionisation produced by particles of different ranges; as an example, if $I_0(r) = \frac{K}{r^2}$, (where $K$ is a constant) on performing the integration we find that $I_z = \frac{K}{2z}$. This shows that until more is known about the ionising properties of particles of different energies, and about their energy distribution, the observed rapid increase of ionisation with altitude is as likely to be due to a corpuscular as to a photon radiation. It is therefore worthwhile to attempt to analyse the ionisation depth curve on the basis of a corpuscular theory.

It has been shown by B. Gross (Zeitschrift für Physik 83, 214, 1933) that an intensity-depth curve $J(z)$, for radiation
entering a medium with equal intensity in all directions, can be converted into a curve \( \mathcal{J}(z) \) representing the intensity as a function of depth, if the radiation were incident in a parallel beam. The relationship is

\[
\mathcal{J}(z) = J(z) - z \frac{dJ(z)}{dz}
\]

It is deduced as follows: Suppose radiation reaches a point at a depth \( x \) in directions lying within a cone of half angle \( \theta_0 \) (Fig. 30). It is necessary to assume again, just as in deducing the \( \mathcal{P}(\mu z) \) law, that the secondary particles directly causing ionisation have the same direction as their primaries, then if \( \mathcal{J}(z) \) represents the intensity of a parallel beam at a depth \( z \), the intensity due to rays coming in directions lying within the limits of the small solid angle \( d\theta_0 \) inclined at \( \theta_0 \) to the vertical, is

\[
\delta J(z) = \text{const.} \int_0^{\theta_0} \mathcal{J}(x \sec \theta) \sin \theta \, d\theta
\]

\[
J(z) = \text{constant} \int_0^{\theta_0} \mathcal{J}(x \sec \theta) \sin \theta \, d\theta
\]

Since \( z \) is constant for the integration, \( z \sec \theta \) may be replaced by one variable, say \( y \). On making this substitution we find

\[
\frac{J(z)}{z} = \text{constant} \int_{y = z}^{y = z} \frac{\mathcal{J}(y)}{y^2} \, dy
\]
Let us represent the integral \( \int \frac{\varepsilon(y)}{y^2} \) by the symbol \( F(y) \).

Then we have

\[
J(z) = F(z \sec \theta_o) - F(z)
\]

Differentiating with respect to \( z \)

\[
\frac{\partial J}{\partial z} - J(z) = \frac{\varepsilon(z \sec \theta_o) \sec \theta_o}{Z^2} - \frac{(z)}{Z^2}
\]

or

\[
J(z) = z \frac{\partial J}{\partial z} = \varepsilon(z) - \cos \theta_o \varepsilon(z \sec \theta_o)
\]

For the free atmosphere, \( J_o = \frac{\pi}{Z^2} \)

\[
J(z) - z \frac{\partial J}{\partial z} = \varepsilon(z)
\]

Although Gross claims that his argument is valid whatever the function \( \varepsilon \), yet in the case of \( r \) particles Compton admits there is some doubt as to its applicability. The reason presumably is that the function \( \varepsilon \) may be discontinuous, but if we are dealing with a continuous distribution of ranges, \( \varepsilon \) is a continuous function, and the procedure seems to be rigid for this case. If we accept this, it is possible at once to obtain the range distribution function \( R(z) \), i.e. the number of particles of range between \( z \) and \( z + \text{dz} \). The decrease in intensity of a parallel beam over the distance \( \text{dz} \) in the medium is proportional to the number of particles coming to the end of their range in \( \text{dz} \). That
**Fig. 31**

Depth in air in cm$^3$ mercury.

**Fig. 32**

Range in air in cm$^3$ mercury.
is, proportional to $R(z)$ and to $dy$, and we may write

$$ R(z) \ dy = -d \mathcal{P}(z) $$

$$ \Rightarrow R(z) = -\frac{d\mathcal{P}}{dz} = z \frac{d^2\mathcal{P}}{dz^2} $$

Compton has plotted the curve $\mathcal{P}(z)$ (actually log $\mathcal{P}$) for his own and for other atmospheric ionization depth curves, see fig. 30 and by obtaining the slope at every point is able to plot the range distribution curve, fig. 31. Two different groups are evident, $A$, having ranges possibly of all values, with a maximum number at the low energy end, and the other $B$ has no range less than 27 cms. mercury and a strong maximum at about 35 cms. mercury. Compton explains peak $B$ as due to electrically charged particles with a wide range of energies, cut off at the low energy end by the magnetic barrier. Störmer's theory shows that electrons coming vertically downward at the latitude of the experiment must have energy at least $2 \times 10^9$ electron volts, and Lemaitre and Vallarta give $1.6 \times 10^9$ as the least energy necessary for a proton. It is very difficult at present to decide either from theoretical results or from experimental measurements of Anderson of energy loss of charged particles in matter, whether either protons or positrons of these energies would be able to penetrate to a depth in the atmosphere of 36 cms. mercury, and in this way to make a decision as to whether group $B$ consists of protons or
positrons. However, if it consists of positrons, then it becomes possible on the basis of theoretical calculations of Bethe, to account for the great ionisation observed high in the atmosphere. Bethe has shown that the rate of loss of energy of high energy electrons increases rapidly with the energy, due to the increasing importance of collisions resulting in the emission of radiation. Therefore high energy electrons will lose energy rapidly, and be accompanied by abundant secondary radiation, which will bring about the intense ionisation, being absorbed by shower production. This has just been pointed out in a letter to *Nature* (13, 734, 1934) by Compton and Bethe. In the same letter they suggest that component A may consist of either photons or $\alpha$ particles; Blackett has shown there is a close correspondence between its rate of absorption and that of the shower producing radiation, which makes the photon hypothesis likely, yet on the other hand, if the great difference between the recent atmosphere curve of Millikan, Bowen and Neher, and those of Regener and Piccard at slightly lower magnetic latitudes is due to a latitude effect, then the particles of range group A must be charged, and because of their low range, may be $\alpha$ particles.

Another analysis of the depth ionisation curves has been carried out by Eckart (*Phys. Rev.* 45, 851, 1934) who finds two
components of absorption coefficient roughly 0.6 and 0.06. The former corresponds to group B of Compton's analysis, and the latter is a group ten times as penetrating, which Compton suggests may be due to protons, because recent theories have shown that for protons, energy loss by radiative collisions is negligible in comparison with that lost by electrons in the same way, so protons must have much longer ranges. If the third component C is due to protons, another experimental observation can be easily explained, namely, the increase with altitude in the ratio of frequency of showers to frequency of coincidences. The coincidences will be partly due to protons, the number of which does not increase rapidly with altitude, while the showers are due only to the positrons, which have a much larger absorption coefficient and therefore show a rapid increase with altitude.
Investigations with Geiger-Müller Tube Counters.

In 1929 a paper was published by W. Bothe and W. Kolhörster entitled "Das Wesen der Höhenstrahlung" (Zeitschrift für Physik 56, 751, 1929). The authors pointed out that, although most workers on the "Höhenstrahlung" regarded it as a very hard $\gamma$ radiation, yet the experimental facts could also be accounted for by a very penetrating electron radiation. In particular, Skobelzyn had found in 1927 (Zeits. für Phys. 43, 371, 1927; 54, 686, 1929) that among the tracks he had photographed in a Wilson expansion chamber, there were some which were not of radioactive origin, of energy (determined by their "Steifheit" in a magnetic field) at least $1.5 \times 10^7$ electron volts. Skobelzyn suggested that these tracks were due to particles as penetrating as the cosmic radiation was known to be, and that therefore these might be associated with it. Bothe and Kolhörster then ask the question, "Ist diese Korpuskularstrahlung als Sekundarstrahlung einer $\gamma$ Strahlung aufzufassen, wie bisher üblich, oder stellt sie selbst die Höhenstrahlung dafü?

They tried to obtain an answer by measuring the absorbability of the corpuscular radiation by the method of coincidences using two Geiger-Müller tubes. They had discovered already that if two Geiger-Müller tubes were placed one above the other, then of the discharges in both tubes, far more occurred simultaneously in
each than could be put down to mere chance, and they suggested that these "systematic coincidences" (the number remaining after the chance coincidences had been subtracted) might be caused by the passage of one and the same corpuscular ray through both tubes. They found that the introduction of a lead block 4 cms. thick between the tubes did not appreciably decrease the number of coincidences, but that a block of gold 4.1 cms thick did cause a decrease just greater than the "statistischen Fehler", if the coincidences were caused by radiation which had not been hardened by passing through floors of the building. They obtained a value for the mass absorption coefficient (assuming simple exponential absorption) and found

\[ \frac{\mu}{\rho} = (3.5 \pm 0.5) \times 10^{-3} \text{ cm}^2/\text{qm} \]

Thus they showed that a value could be obtained for the absorption coefficient of the corpuscular radiation, which was of the same order of magnitude as those found for the penetrating radiation itself by absorption measurements in lakes.

The next advance was made in 1931 by an Italian, Bruno Rossi, (Zeits. für Phys. 68, 65, 1931) Using the same arrangement as Bothe and Kolhörster, and a lead absorbing screen 9.7 cms thick, he showed that the mass absorption coefficient of the radiation (already hardened by "filtering" through 5 cms. of lead) was

\[ \left( \frac{\mu}{\rho} \right)_K = (1.6 \pm 0.3) \times 10^{-3} \text{ cm}^2/\text{qm} \]
\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig31}
\caption{Fig. 31}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig32}
\caption{Fig. 32}
\end{figure}
More important than this, he discovered that when the absorbing screen was above the counters, there were more systematic coincidences than when it was between the two tubes, and he suggested that this could be explained by the production of secondary corpuscles in the lead. In his next paper (Zeits. für Phys. 82, 151, 1933) Rossi showed

1. that about 50% of the corpuscular rays had a range greater than a metre of lead; this was the result of counting triple coincidences, the experimental arrangement being such that the corpuscles passing through the three counters traversed a total thickness of 101 cms. lead. The number of triple coincidences amounted to $1.166 \pm 0.059$ per hour, and the counting extended over 347 hours.

2. that groups (showers) of secondary corpuscles were ejected from metals by the passage of the corpuscular radiation through them.

**Showers.**

The arrangement of the counters is shown in Fig. 3. The thickness of the lead screen A was varied, and the number of triple coincidences plotted as a function of the thickness of the lead. Three curves were obtained (Fig. 32) two for lead screens at two different distances from the two upper tube counters, and one for an iron screen. All three curves show an initial rise
Fig 33

1 - With lead side screens
2 - Without
3 - Difference (triple coincidences arising from screens)
in the number of coincidences, and a subsequent falling off.
The explanation given by Rossi is as follows: the coincidences
are caused by showers of secondary corpuscles ejected from the
lead. These corpuscles are charged, and therefore have a definite
range in the lead. When the thickness of the absorber exceeds
the range of the secondary corpuscles, those formed in the first
few centimetres do not emerge from the lead, and hence the curve
showing the number of coincidences begins to fall off; the
thickness of the lead at which the maximum number of showers is
reached must be the range of the shower particles in lead, and
is between one and two centimetres. The absorption coefficient
calculated from the falling part of the curve is that of the
radiation directly responsible for the showers.

A month after Rossi's paper had appeared, Fünfer published
results which confirmed those of Rossi, and brought to light
another interesting phenomenon (Zeits. für Phys. 83, 92, 1933).
Fünfer discovered that the presence of side screens round the
tube counters caused an increase in the number of triple coin-
cidences. Figs. 33 and 34 show his measurements. The difference
in the two curves (Fig. 33) with and without side screens gives
the number of particles coming from them, and this number is seen
to depend on the thickness of the lead above the tubes, being
greatest when the upper screen is 1.6 cms thick as before.
Fig 34

Triple Coincidences due to Side Screens of Varying Thickness

Fig 35

To show showers arising in lower screens.

Fig 36.

Curve 1 - with upper screen

2 - without
Fig. 34 shows the number of coincidences when the thickness of the lead side screens was varied, the screen above being 1.6 cms thick throughout the experiment. The number rises until the side screens are 0.6 cm thick and then remains constant. Thus Fünfer considers that often secondary corpuscles striking the side screens are deflected back to the counters, and add to the possibility of coincidences. He carried out another experiment, showing that the angle of scattering of the secondary corpuscles may be very large. The arrangement is shown in Fig. 35.

Counts were taken with and without the upper lead screen; Fig. 36 shows the result. Again the number of coincidences increased until the lower screen was 0.6 cm thick, and greater thickness had no further effect. Fünfer's view is that these particles are secondary corpuscles scattered in a backward direction by the side screens and the lead below the tubes. Blackett and Gilbert, however, who have noticed the same effect, consider that some component of a shower is able to produce another shower in lead, since cloud chamber photographs show that if a shower occurs there is a large chance that another occurs near to it. Gilbert's experiments have been carried out at the Forschungs station, Jungfraujoch (3,500 m), at Eigergletscher (2,330 m) and at Zurich (500 m), to investigate the frequency of showers at different altitudes. On the Jungfraujoch a curve was obtained
Fig. 37

Showers per hour

<table>
<thead>
<tr>
<th>Thickness of lead</th>
<th>Showers due to different lead screens of different thickness above the counters</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 cm lead</td>
<td></td>
</tr>
<tr>
<td>4 cm lead</td>
<td></td>
</tr>
<tr>
<td>6 cm lead</td>
<td></td>
</tr>
<tr>
<td>8 cm lead</td>
<td></td>
</tr>
</tbody>
</table>

Altitude 3500m
like those already described, with one notable difference: the maximum number of coincidences occurred when the lead above the tube counters was 2.0 cms thick (Fig. 37) After subtracting the showers counted without the lead screen (originating in the atmosphere) the fall away from the maximum is exponential with a coefficient $\mu = 0.38 \text{ cm}^{-1}$. This must represent the absorption coefficient of the radiation producing the showers; it is much greater than the values given for the primary penetrating radiation, and therefore Gilbert infers that the showers are produced by a radiation which is not the primary, but is very much more absorbable.

**Origin of the Shower Particles.**

Fünfer explains the high absorption coefficient by supposing that the showers are caused by a weak component of the primary radiation, coming chiefly in a vertical direction, but this has been disproved by Johnson, who has measured the numbers of showers emerging from a lead screen with his apparatus arranged as in Fig. 38 (Instead of a single Geiger-Müller tube, Johnson uses a bundle consisting of three separate counters, the advantage being that the total counting rate of the three, because of their small size, is less than that of a single counter of the same cross section, and therefore the chance of a corpuscular ray not being recorded during the insensitive time of recovery of
a counter, is very much less. Johnson's triple coincidences were 
therefore measured with three bundles of three counters, each 
bundle behaving in the same way as, though more efficiently than, 
a single counter). The block of lead was inclined at an angle 
of 30° to the horizontal, and the apparatus was rotated about a 
vertical axis between the east and west azimuth. Johnson finds 
that the counts due to the lead were 1.03 per minute from the 
east, and 1.11 per minute from the west, giving a west excess of 
0.08, and showing an asymmetry of the same order as that he ob­
served at the same place (Peru, on the geomagnetic equator) for 
the total corpuscular radiation (observed by counting linear 
triple coincidences). This is very powerful evidence that the 
showers owe their origin in the first instance to the primary 
charged corpuscular radiation; the experiments of Rossi, Fünfer 
and Gilbert show that they are not produced directly by it, but 
are immediately due to a much softer radiation. This cannot be 
part of the incoming radiation, for its absorption coefficient, 
0.38 per cm. lead, is much too large to allow it to penetrate 
the atmosphere, so that it must be generated by primary corpuscles, 
in their passage through matter. Gilbert and Bhabha, assuming 
the showers are due to a secondary radiation which has a smaller 
equilibrium intensity in lead than in air, have obtained expres­
sions for the number of showers emerging from lead. The theory 
agrees well with the experimental results, and it is difficult to 
see how else the shower curves can be explained, except on the
assumption that they are produced by a secondary radiation whose equilibrium intensity is upset on passing from one medium to another.

Gilbert, Johnson, and Rossi have each compared numbers of showers at different altitudes. Gilbert finds that the ratio is the same as the ratio of the total corpuscular radiations at the two altitudes, but Johnson finds that at a depth in the atmosphere equivalent to 6 metres of water, the number of showers is 6.9 times the number at sea level, while the total corpuscular radiation (measured by linear triple coincidences) is only 3.73 times the sea-level value. Rossi too finds that the ratio of frequency of showers to frequency of coincidences increases with altitude. If Johnson and Rossi are right, it means that the corpuscular radiation producing the showers is more easily absorbed than the general radiation. Since Johnson's apparatus discriminates in favour of showers produced by vertical rays, he calculates the absorption coefficient of the corpuscular radiation producing the showers by the simple exponential law:

$$\frac{I_1}{I_2} = e^{-\mu(h_1 - h_2)}$$

where $I_1$ and $I_2$ are the shower rates observed at the depths in the atmosphere $h_1$ and $h_2$. His data taken without a lead screen give the value $\mu = 0.50$, and with a 1.5 cm. lead screen give a
value 0.49. Here again is further evidence that the charged
corpuscular component is responsible for the showers, for
White Johnson, as already described, calculated the absorption co-
efficient of the corpuscular component from measurements of the
asymmetry and found it was about 0.52 per metre.
Störmer's Theory of the Paths of Charged Corpuscles moving in Earth's Magnetic Field.

If the penetrating radiation which comes into the earth's atmosphere from far-off space is a charged corpuscular radiation, (as is suggested by experiments with Geiger-Müller tube counters) then each charged particle will be under the influence of a force due to the earth's magnetic field, and its path will be bent into a curve. Moreover, the energy of the particle and its direction in space when very far off, decide at what latitude and in which directions it may arrive on the earth. A theory of the paths of charged corpuscles in the earth's magnetic field was developed by Carl Störmer (Oslo University Observatory) in 1904, in connection with the phenomena of the Aurora Borealis, and he has recently applied his theory to the problem of cosmic radiation; with its aid the variation in intensity of the radiation with latitude, and the azimuthal asymmetry can be explained.

Störmer assumes that the earth's magnetic field is that of a dipole, the geomagnetic axis being the diameter through Smith Sound, north west of Greenland (78° N 76° W); the paths of charged particles in the field are governed by the laws of electro-magnetism, there being no other force acting on the particles except that due to the magnetic field.

Let the centre of the earth be taken as the origin O of rectangular co-ordinates OX, OY, OZ, the directions of the axes
being fixed by the usual convention, that if any axis is turned so that it takes up the same direction as the axis which comes next in the order XYZ, about the third axis, then the positive direction of the third axis is given by the direction of forward motion of a right-handed screw turned as just described (Fig. 32). In Störmer's paper this convention is not adopted but its adoption in what follows enables the expressions for the force on a charged particle to be written down in their usual form. Let the intensity of the magnetic field at any point P, (xyz) be $H$ gauss, and let the velocity of a particle at $P$ be $v$ cms/sec, and its charge be $e$, in electro-magnetic units, where $e$ may be positive or negative.

The force on the charged particle is then:

$$ F = e \left[ \mathbf{v} \times \mathbf{H} \right] $$

the square bracket signifying the vector product of v and H.

The $x$ component is

$$ F_x = e \left( v_y H_z - v_z H_y \right) = \frac{d}{dt} \left( m v_x \right) $$

$$ = m \frac{d}{dt} v_x + v_x \frac{e}{m} \frac{d}{dt} $$

Since the force is always perpendicular to the velocity, the numerical value of $v$ does not change, and therefore

$$ \frac{dv}{dt} = 0 $$
\[ F_x = e \left( v_y H_z - v_z H_y \right) = m \frac{d^2x}{dt^2} \]  

where \( m \) is constant, but not necessarily the rest mass.

Similarly

\[ F_y = e \left( v_x H_z - v_z H_x \right) = m \frac{d^2y}{dt^2} \]
\[ F_z = e \left( v_x H_y - v_y H_x \right) = m \frac{d^2z}{dt^2} \]

The components of \( H \), the intensity of the magnetic field of a dipole at \( P \) (xyz) are

\[ H_x = -\frac{M}{r^5} \left( 3x y \right) ; \quad H_y = -\frac{M}{r^5} \left( 3y z \right) ; \quad H_z = -\frac{M}{r^5} \left( 3z^2 - r^2 \right) \]

where \( M \) is the magnetic moment of the dipole, and \( r \) the radius vector to the point \( P \). Störmer uses a new variable \( s \), which is a length measured along the track of the particle.

\[ ds = v dt, \]
\[ \frac{dx}{dt} = \frac{ds}{dt} \frac{dx}{ds} = v \frac{dx}{ds} \]
\[ \frac{d^2x}{dt^2} = v \frac{d^2x}{ds^2} \frac{ds}{dt} = v^2 \frac{d^2x}{ds^2} \]

Equation (1) becomes

\[ m v^2 \frac{d^2x}{ds^2} = e \nu \left( -\frac{3z^2 - r^2}{r^5} \frac{dv}{ds} + \frac{3y^2}{r^5} \frac{dz}{ds} \right) \]

Let \( e^1 \) be the positive numerical value of \( e \), so that \( e = \pm e^1 \) according as to whether we are concerned with positive or negative
particles. Write $c^2$ for $\frac{\hbar c}{mv}$. The quantity $\sqrt{\frac{\hbar c}{mv}}$ has the dimensions of length, and if we choose $\sqrt{\frac{\hbar c}{mv}}$ cms. as our unit of length, we can write

$$\frac{d^2x}{ds^2} = \pm \left( -\frac{3e^2 - r^2}{r^3} \frac{dv}{ds} + \frac{3e}{r^3} \frac{dx}{ds} \right) - - - - (4)$$

$$\frac{d^2y}{ds^2} = \pm \left( -\frac{3e}{r^3} \frac{dz}{ds} + \frac{3e^2 - r^2}{r^3} \frac{dx}{ds} \right) - - - - (5)$$

$$\frac{d^2z}{ds^2} = \pm \left( -\frac{3e}{r^3} \frac{dx}{ds} + \frac{3e}{r^3} \frac{dy}{ds} \right) - - - - (6)$$

In passing it may be pointed out that the unit of length $\sqrt{\frac{\hbar c}{mv}}$ cms. depends on $mv$, and therefore on the energy of the charged particle, and the radius of the earth measured in these units, will have different numerical values for electrons of different energies.

Introduce now cylindrical co-ordinates $x = R \sin \phi$, $y = R \cos \phi$ (see Fig. ) It can be shown, by differentiating $x$ and $y$ with respect to $s$, that

$$x \frac{dx}{ds} + y \frac{dy}{ds} = R \frac{dR}{ds} \quad (7)$$

$$y \frac{d^2x}{ds^2} - x \frac{d^2y}{ds^2} = \frac{d}{ds} \left( R^2 \frac{d\phi}{ds} \right) \quad (8)$$

Making use of the identities (7) and (8) to combine equations (4) and (5), we obtain:
\[
\frac{d}{ds} \left( R^2 \frac{d\phi}{ds} \right) = \frac{d}{ds} \left( \frac{R^2}{r^3} \right)
\]

where the minus sign now refers to a positive particle, and the plus sign to a negative particle. After integration, we have

\[ + r^2 \frac{d\phi}{ds} = 2\sqrt{1 + \frac{R^2}{r^3}} \]  

\( \phi \) is an integration constant which can have all values from \(-\infty \) to \(+\infty \). When the particle is infinitely distant,

\[ 2\sqrt{1 + \frac{R^2}{r^3}} = -\frac{R^2}{ds} \]

which may be written

\[ 2\sqrt{1 + \frac{R^2}{r^3}} = \frac{\frac{R^2}{ds}}{\frac{R^2}{ds}} + \frac{R^2}{v} \]

where \( w \) is the angular velocity of the projection of the particle on the XY plane, and \( R^2w \) proportional to the angular momentum of the projection about the centre of the earth. Thus the distribution of \( \sqrt{ } \) values among the particles will be related to the distribution of direction among them, and since, as far as we know, there is perfectly uniform distribution of direction, the number of particles having \( \sqrt{ } \) value lying between \( \sqrt{ } \) and \( \sqrt{ } + d\sqrt{ } \) will be proportional only to \( d\sqrt{ } \).

A further advance can be made by using the relationship

\[ ds^2 = dx^2 + dr^2 + R^2d\phi^2 \]

(See Fig.  ).
Dividing by $ds^2$ and rearranging, we have

$$1 - R^2 \left( \frac{d\phi}{ds} \right)^2 = \left( \frac{dz}{ds} \right)^2 + \left( \frac{dr}{ds} \right)^2$$

With the aid of equation (9), $\frac{d\phi}{ds}$ may be eliminated, and the result is

$$1 - \left( \frac{\frac{d\phi}{R} + \frac{hr}{r^3}}{r} \right)^2 = \left( \frac{dz}{ds} \right)^2 + \left( \frac{dr}{ds} \right)^2$$

Let us write $Q$ for the right-hand side of this equation.

$$Q = \left( \frac{dz}{ds} \right)^2 + \left( \frac{dr}{ds} \right)^2$$

Then using equation (6) we can show that

$$\frac{d^2z}{ds^2} = \frac{1}{2} \frac{\partial Q}{\partial z} \quad \quad (10)$$

And using equations (4) and (5)

$$\frac{d^2r}{ds^2} = \frac{1}{2} \frac{\partial Q}{\partial r} \quad \quad (11)$$

Equations (10) and (11) hold for both positive and negative particles without change of sign.

The motion of the particles is thus analysed into two independent movements, the turning of the meridian plane round the $z$ axis, given by (9), and the movement of the particle in this plane, given by (10) and (11).
The Forbidden Spaces.

Since \( q \) is equal to \( \left( \frac{dz}{ds} \right)^2 + \left( \frac{dr}{ds} \right)^2 \), it is never negative.

\[
\left( \frac{2v}{r} + \frac{r}{r^2} \right)^2 \leq 1
\]

\[-1 \leq \frac{2v}{r} + \frac{r}{r^3} \leq +1 \text{ (12)}
\]

For a particle of given energy (which fixes the unit of length and therefore the numerical value of \( R \) and \( r \) at a place) the conditions (12) holds for certain parts of space depending on the value of \( v \). Let the part of space where (12) holds be called \( Qv \), then the tracks fall into a series of families of which each family is characterised by a special value of \( v \), all enclosed in the space \( Qv \).

The space \( Qv \) is found as follows:

The equation \( \frac{2v}{r} + \frac{r}{r^3} = K \) (13)

represents a curve in the meridian plane. If \( R \) is given all values from +1 to -1, a family of curves is obtained, covering an area of the meridian plane. \( Qv \) is obtained when this area is rotated about the \( z \) axis.

In Fig. 5 the curve (13) is drawn for the family \( v = -1 \), the members of the family for which \( K = +1, K = -1 \), being
No curves for which \(-1 < k < +1\) lie in the part painted in.

\[
\begin{align*}
&\text{Fig 40} \\
&k = \frac{\frac{2}{\text{sec}^2 \lambda} + \cos \lambda}{\frac{1}{\text{sec}^2 \lambda}} \\
&\gamma = -1 \\
&\text{Fig 41} \\
&k = -\frac{1}{\text{sec}^2 \lambda} + \frac{\cos \lambda}{\gamma^2} \\
&\gamma = -0.5
\end{align*}
\]
plotted. Curves for which \( 1 > K > -1 \) lie in the unshaded part of the figure. Fig. 4\( _4 \) shows the same for the family \( \sqrt{V} = -0.5 \). Fig. 5. is reproduced from Stürmer's paper (Gerland's Beiträge zur Geophysik. Supplement Band I. Ergebnisse der Kosmischen Physik). It shows sections in a meridian plane of the forbidden spaces (shaded) into which corpuscles of the respective \( \sqrt{V} \) values cannot penetrate. It is seen from this figure, that for values of \( \sqrt{V} \) algebraically smaller than \(-1\), \( \sqrt{V} \) consists of two separate parts, and no tracks from infinity can reach the earth unless the energy of the corpuscle is so large that a part of the earth's surface lies outside the shaded area. In other words, \( \sqrt{V} = -1 \) is a limiting value; it is for this value of \( \sqrt{V} \) that electrons of relatively small energy can just begin to arrive at the earth from infinity. No rays with \( \sqrt{V} \) value algebraically less than \(-1\) can reach the earth unless their energy is greater than that which makes the radius of the earth one unit in the special units chosen. (See Fig. 4\( _2 \)) Before going further, it will be helpful to calculate the numerical value for the radius of the earth, for electrons of various energies. The figures in Table I are calculated in the following way. The unit of length is \( \sqrt{\frac{M_1}{mV}} \), where \( M \) is the earth's magnetic moment, and is taken as \( 8 \times 10^{25} \) e.m.u., \( e_1 \), \( m \), and \( v \) are the charge (numerical value), mass, and velocity of the
Spaces \( \gamma \), into which all tracks of given \( \gamma \) value are confined.

Forbidden spaces black on right, left of diagram, shaded on right.
particle considered. If its path is bent by a magnetic field \( H \), then

\[
H e V = \frac{m v^2}{\rho}
\]

where \( \rho \) is the radius of curvature of the track.

Or, \( H \rho = \frac{m v}{e} \), and the unit of length becomes

\[
\sqrt{\frac{H}{\rho}} = \sqrt{\frac{330 \, M}{V}}
\]

where \( V \) is the energy in electron volts.

Table shows the value in centimetres of this unit for electrons of various energies, and the corresponding numerical value for the radius of the earth.

<table>
<thead>
<tr>
<th>Unit of length (in cms.)</th>
<th>Energy ( V ) of electron (electron volts)</th>
<th>Radius of earth in given units (proportional to ( \sqrt{V} ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.4 ( \times 10^9 )</td>
<td>6 ( \times 10^8 )</td>
<td>0.10</td>
</tr>
<tr>
<td>3.2 ( \times 10^9 )</td>
<td>2 ( \times 10^9 )</td>
<td>0.20</td>
</tr>
<tr>
<td>2.3 ( \times 10^9 )</td>
<td>4 ( \times 10^9 )</td>
<td>0.23</td>
</tr>
<tr>
<td>1.6 ( \times 10^9 )</td>
<td>1 ( \times 10^{10} )</td>
<td>0.41</td>
</tr>
<tr>
<td>1.1 ( \times 10^9 )</td>
<td>2 ( \times 10^{10} )</td>
<td>0.60</td>
</tr>
<tr>
<td>6.4 ( \times 10^8 )</td>
<td>6 ( \times 10^{10} )</td>
<td>1.00</td>
</tr>
<tr>
<td>4.9 ( \times 10^8 )</td>
<td>1 ( \times 10^{11} )</td>
<td>1.31</td>
</tr>
<tr>
<td>1.55 ( \times 10^8 )</td>
<td>1 ( \times 10^{12} )</td>
<td>4.15</td>
</tr>
</tbody>
</table>
Fig 43
Turning to Fig. 3 again, if the energy of the electron is \( 6 \times 10^{10} \) volts, the radius of the earth is 1.0, and the electron can just get in at the equator from infinity. From Fig. 3, it is clear that electrons of very much smaller energies can arrive if their \( \gamma \) values lie between 0 and -1. As energies greater than \( 6 \times 10^{10} \) volts are in practice impossible to measure, since they require magnetic fields beyond the resources of laboratories, in what follows only those particles will be considered with \( \gamma \) value between 0 and -1, and maximum energy \( 6 \times 10^{10} \) volts. The magnetic field required to give the path of a particle of this energy a radius of curvature of 1000 cm, is \( 2 \times 10^5 \) gauss.

The highest energy yet measured by C.D. Anderson, is \( 6 \times 10^9 \) volts with a field of \( 1.5 \times 10^4 \) gauss.

The meaning of \( K \).

Equation (2) states

\[
- \frac{R}{z^3} \frac{d\phi}{ds} = \frac{2\gamma}{r} + \frac{B}{r^3}
\]

\(-\) sign refers to positive particles
\(+\) sign refers to negative particles

The left hand side of this equation is the quantity \( K \) which is limited by the theory to values lying between -1 and +1. In Fig. 6, let \( \hat{\theta} \) be the angle between the tangent at \( P \) to the track of the particle, and the meridian plane through \( P \). \( PT \) is the tangent, \( TN \) is normal to the meridian plane, and \( \angle TPN = \hat{\theta} \)
Sections of the space $Q_Y$ near the dipole and the forbidden "torus-like" spaces.
Let $\theta$ be positive if the particle comes through the meridian plane from east to west, otherwise negative. In Fig. 44, let $PT$ represent a short length $ds$ of the track at $P$. Then

$$\sin \theta = \frac{TH}{PT} = \frac{Pd\phi}{ds}$$

Thus $K = \mp \sin \theta$, and $\theta$ is the angle between the track of the particle and the meridian plane. We may therefore write the equation for the track

$$+ \sin \theta = -\frac{2V^1}{r \cos \lambda} + \frac{\cos \lambda}{r^2}$$

This equation, referring only to negative electrons, and therefore with only the plus sign in front of $\sin \theta$, was given by Stürmer in 1907. (Archives des sciences phys. et natur. 24, 1907).

**Discussion of equation.**

Particles of $\gamma$ value between 0 and -1 are limited to a space $Q\gamma$, which extends from infinity to the centre of the magnet. Situated symmetrically round the equator is a torus-like "forbidden" space (see Fig. 45) but $Q\gamma$ extends, between the torus and the upper and lower spindle shaped spaces, to the centre of the earth, and cuts the earth in a belt, within which therefore, particles of given energy and given $\gamma$ arrive. They come in at the highest latitude of the belt when $K = -1$ (See
Fig. 42. Now for positive particles

\[ \mathbf{x} = - \sin \theta \]

therefore \( \theta = 90^\circ \). They come in at lowest latitudes for \( k = +1 \), or \( \theta = -90^\circ \) for positive particles. Thus positive particles of given energy and given \( \psi \) value come in at highest latitudes at glancing angle from the east, and at lowest latitudes at glancing angle from the west. Fig. is reproduced from Störmer's paper, and shows sections of the space \( \psi \) near the dipole. If a circle representing a section of the earth is drawn round the centre of the figure, \( \psi \) cuts the section at lowest latitudes when \( \psi = -1 \). This means that for electrons of given energy, the mean latitude of the belt within which they arrive is least if \( \psi = -1 \); if they are positive particles they will come in at the lowest latitude of the belt at glancing angle from the west, and at the highest latitude at glancing angle from the east, and vice versa for negatives.

The Cone of Possible Directions.

Since \( \theta \) is the angle between the track of a particle and the meridian plane, a given value of \( \theta \) corresponds to a family of tracks, covering the surface of a cone. It is now possible to account for the decrease of the intensity of the radiation towards the equator, and for the azimuthal asymmetry, by an examination of the equation
Possible directions at a given latitude for positive rays of given energy

\[ y' = \frac{1}{2} \left( \frac{\cos^2 \lambda - v \cos \lambda}{W} \right) E \]

Fig 46

Possible directions at a given latitude for positive rays of given \( y \) value.

minimum energy

minimum energy

maximum energy

maximum energy

Fig 47
\[
\sin \theta = -\frac{2V^1}{r \cos \lambda} + \frac{\cos \lambda}{r^2}
\]

The following deductions can be made, which refer to positive particles.

1. Consider first a particle of given energy \(r\) fixed), arriving at a given latitude \(\lambda\). We have

\[
\sin \theta = -\frac{2V^1}{r \cos \lambda} + \frac{\cos \lambda}{r^2}
\]

or

\[
\sin \theta = -\frac{2V^1}{r \cos \lambda} - \frac{\cos \lambda}{r^2}
\]

Since \(r\) and \(\cos \lambda\) are always positive, the greatest value (algebraically) of \(\sin \theta\) is when \(V^1 = 1\). All values of \(\sin \theta\) algebraically less than this maximum value correspond to smaller values of \(V^1\). Thus we may represent the possible directions as in Fig. 46, in which the greatest value for \(\sin \theta\) is positive, and all the other possible directions lie within a cone, (of semi-vertical angle greater than \(\frac{\pi}{2}\)). The \(V^1\) corresponding to glancing angle from the west (\(\theta = -\frac{\pi}{2}\)) is found to be \(\frac{1}{2} \left( \frac{\cos^2 \lambda}{r} - r \cos \lambda \right)\). If this expression is negative, the given particle cannot arrive at all at this latitude.

2. At a given latitude, and for positive particles of given \(V\) values, the greater \(\sin \theta\) (algebraically) the greater the energy
Possible directions for positive particles of three different energies.

Blue ink - greatest of three energies.
Green ink - intermediate energy value.
Red ink - least energy shown.

Fig 48
For negative particles, the less \( \sin \theta \) (algebraically) the greater the energy.

3. The minimum energy permitted to reach a given latitude in a given direction belongs to those particles with \( \sqrt{\lambda} \) value \(-1\), and combining this with (2) we see that the least energy of all permitted to reach a given latitude is found by putting \( \sqrt{\lambda} = 1 \), and \( \theta = -\frac{\pi}{2} \) in the general equation (see Fig. 10).

4. The minimum energy permitted to arrive at all at a given latitude, increases towards the equator. It is given by the following expression

\[
E_{\text{min}} = -\frac{1 + \sqrt{1 + \cos^3 \lambda}}{\cos \lambda}
\]

and it can be shown that \( \frac{dE_{\text{min}}}{d\cos \lambda} \) is positive. At the equator, \( E_{\text{min}} \) is 0.414, corresponding to an energy of \( 10^{10} \) volts.

5. For energies less than \( 10^{10} \) volts, there is a minimum latitude below which they cannot arrive. At the minimum latitude they can only enter at glancing angle from the west, and for higher latitudes the cone of possible directions widens until it includes all directions in space. At higher latitudes all directions are possible, but the values of \( \sqrt{\lambda} \) are less, the value \( \sqrt{\lambda} = -1 \) being cut out as soon as all directions in space are possible.

6. Within the cone of possible directions for a given energy there is uniform distribution of direction among the particles.
Fig 49

Dependence of intensity on latitude at sea level

O = Northern Hemisphere
□ = Southern Hemisphere
X = Clay, Berlage
+ = Hillikan

Tons cm⁻³ sec⁻¹ at sea level

Geomagnetic Latitude

10° 20° 30° 40° 50° 60° 70° 80° 90°
This follows because the number of particles having a $\sqrt{1}$ value between $\sqrt{1}$ and $\sqrt{1} + d\sqrt{1}$ is proportional only to $d\sqrt{1}$. Thus the energy distribution of particles in a given direction if there were no atmosphere present, would be the same as the energy distribution of the radiation before it is influenced by the earth's magnetic field; actually all rays of energy less than that required to penetrate the atmosphere in the given direction are absorbed in the atmosphere.

The same statements apply to negative particles if everywhere the word west is changed for east, and east for west. The direction of a negative particle is a reflection in the meridian plane of the direction of a positive particle of the same energy and $\sqrt{1}$ value.

**The Latitude Effect.**

The latitude effect was first discovered by J. Clay in 1927 (Proc. Amsterdam Academy 30, p. 1115, 1927) on a voyage from Java to Holland, and confirmed by Compton and his collaborators (Phys. Rev. 43, 387, 1933). Figures 12 and 13 are taken from Compton's paper; the curves show the increase of the intensity with latitude from the equator up to about latitude 50°, after which the intensity is independent of latitude. The percentage increase is greater the higher the altitude at which the measurements are made. The data in every case were obtained with ionisation.
Fig 50

Latitude effect at different altitudes

Barometer 101.3 cm
Altitude 4350 m

Barometer 60 cm
Altitude 2000 m

Barometer 76 cm
Altitude 0
chambers. Compton's instruments were filled with argon at 30 atmospheres pressure, and were all calibrated, using the same radium standard, so that measurements taken by the eight expeditions organised by Compton, at sixty-nine representative points over the earth's surface, could be compared. In the last few months other investigators (B. Rossi, H. Hörlin, P. Auger and L. Legéndre Ringnet) have also shown that the intensity of the cosmic radiation diminishes towards the geomagnetic equator, so the latitude effect can now be regarded as an established experimental fact.

Explanation of the Latitude Effect.

Störmer's theory shows that the minimum energy permitted to reach a given latitude increases towards the equator. Starting from the equator, therefore, and proceeding to higher latitudes, rays of smaller and smaller energy are able to arrive, while those of high energy are not cut out, but have different and smaller $\sqrt{1}$ values. Thus one would expect, assuming a range of energies present in the primary radiation, an increase in the intensity towards higher latitudes due to the arrival of more and more rays of lower energy. The reason for the steady value of the intensity at latitudes higher than about 50°, is to be found in the absorption effect of the earth's atmosphere. If a ray travelling in the vertical direction is completely absorbed by
a given depth of the atmosphere, then no rays of the same energy whatever their direction, will penetrate to that depth. According to Bethe's calculation (mentioned earlier) for electrons of energy $10^8$ volts, it requires about $3 \times 10^9$ electron volts to penetrate vertically to sea-level; Anderson's estimate is a little higher, namely, $5 \times 10^9$ electron volts. Taking a mean value of $4 \times 10^9$ electron volts, corresponding to $r = 0.28$, we can find the minimum latitude at which rays of this energy can arrive vertically downwards, i.e. substitute $\theta = 0$, $\sqrt{1} = 1$, $r = 0.28$, in the general equation. We find $\lambda = 41^0 30'$, and one would expect no further increase in the intensity due to the arrival of less energetic rays at higher latitudes. Compton's curves show that the increase continues up to about latitude $50^0$, which may be due to the widening of the cones of allowed directions for rays of greater energy, between latitudes $40^0$ and $50^0$, or it may mean that rather less energy than $4 \times 10^9$ electron volts is necessary to penetrate the atmosphere. Bethe's calculation holds for electrons of energy $10^8$ volts, so it is possible that electrons of higher energy may lose less energy in passing through matter than the value Bethe gives, but there is no experimental evidence for this; Anderson's experimental work indicates a rather higher energy loss. An important feature which one would expect of curves showing latitude effect at
Fig 51

Latitude effect at high altitudes but not at sea level.
different altitudes is absent from Compton’s curves, namely that the greater the altitude, the higher should be the latitude at which the constant value for the intensity first sets in, because low energy rays, only entering at high latitudes are absorbed before they reach sea level, but contribute to the ionisation higher up in the atmosphere. As there is apparently only one of Compton’s measurements which could test this (at 66°, altitude 2000 metres) his curves are too incomplete to bring out this point, but it is shown in two curves published by Bowen, Millikan and Neher giving the intensity-depth relation at Spokane, Washington, magnetic latitude 51° N, and at March Field, California, magnetic latitude 41° N. (See Fig. 5). According to these two curves, the steady value for the intensity has already set in at 41° N, at sea level, which is what the theory leads one to expect.

Comparison of Latitude Effect with Results of Measurements.

T. H. Johnson has shown (Phys. Rev. 45, 509, 1334) how the magnitude of the latitude effect may be calculated from the theory. Suppose measurements of the intensity of the radiation are taken in a given direction $\theta^0$ west of the vertical at two different latitudes. In order to simplify the calculations, suppose that there is uniform distribution of energy among the particles. Then of the total intensity, $J(\mathbf{v}, \theta)$, that fraction
which is due to positive rays of energy corresponding to $r$
values between $r$ and $r + \, dr$, may be written $J_+ \, dr$, in atmosphere free space. Let $f_+ (\mu z \sec \theta)$ represent the fractional decrease due to atmospheric absorption at depth $z$ in the atmosphere. Then $J_+ f_+ \, dr$ is the fraction of the total intensity in the given direction due to positive rays of the given energy range. Let $r_o (\lambda_1 \theta)$ represent the minimum energy coming in the given direction; all greater energies present in the primary radiation will also be present in the given direction. The total intensity due to positive rays of all energies is therefore

$$\int_{r_o (\lambda_1 \theta)}^{r_{\text{max}}} J_+ f_+ \, dr.$$ 

At latitude $\lambda_2$, a higher latitude, the minimum energy $r_o (\lambda_2 \theta)$ will be less. Thus the difference in intensity due to positives in the given direction will be due to the inclusion at the higher latitude of energies between $r_o (\lambda_1 \theta)$ and $r_o (\lambda_2 \theta)$

The total fractional change in intensity due to positive particles is therefore:

$$\int_{r_o (\lambda_1 \theta)}^{r_o (\lambda_2 \theta)} f_+ J_+ \, dr.$$
There will be a similar expression for the total fractional change due to negatives; the minimum energies, $r_{o}^{-1}(\lambda_{1}\theta)$ and $r_{o}^{-1}(\lambda_{2}\theta)$, will be greater (since $\theta$ is west of the vertical) than for positives. Thus we may write

$$\frac{J(\theta\lambda_{2})}{J(\theta\lambda_{1})} = \int_{f_{+}J_{+} dr}^{f_{-}J_{-} dr} \frac{r_{o}(\lambda_{1}\theta)}{r_{o}(\lambda_{2}\theta)} + \frac{r_{o}^{-1}(\lambda_{1}\theta)}{r_{o}^{-1}(\lambda_{2}\theta)}$$

Since measurements of the azimuthal asymmetry show that the intensity from the west is greater than that from the east, Johnson puts to the test the simplest assumption, that the primary radiation is exclusively positive. The second term in (1), therefore, disappears. In order to carry out the integration of the first term, it is necessary to try an empirical function for $f_{+}J_{+}$. Now Johnson shows in his paper that the expression

$$f_{+}J_{+} = 4e^{-0.167z \sec \theta},$$

(the fractions being fractions of zenith intensity at the equator), enables him to calculate magnitudes of the asymmetry effect which are in good agreement with those observed by him. Using this expression, let us test the observation of P. Auger and L. Leprince Ringuet, mentioned in a paper which they presented.
at the London International Conference on Physics (October 1934) that the vertical intensity is 16% greater at latitude 40° than at the equator. The theoretical percentage increase is

\[
\frac{1}{100} \int_{0.29}^{0.50} 4 \cdot e^{-1.67} \, dr = 16\%
\]

Since \( r_0 = 0.50 \) and \( r_0 = 0.29 \) represent the minimum energies incident vertically at the equator and at latitude 40° respectively, and \( z = 10 \) equivalent metres of water (measurements at sea level) Johnson also quotes their result that the vertical intensity at latitude 29° is 10% greater than at the equator. One would expect a percentage increase of

\[
100 \int_{0.29}^{0.50} 4 \cdot e^{-1.67} \, dr
\]

which turns out to be 9%, again in good agreement. In order to compare theoretical latitude variations with those observed with ionisation chambers, the expression (1) must be averaged over all zenith angles. The following table taken from Johnson's paper shows the result of this comparison.
Comparison of observed latitude-intensity variation (expressed as percentage increases over the value at the equator) with values calculated from asymmetry measurements, assuming an exclusively positive, corpuscular primary radiation.

<table>
<thead>
<tr>
<th>Latitude</th>
<th>Depth (metres of water)</th>
<th>Calculated % increase</th>
<th>Compton</th>
<th>Bowen, Millikan &amp; Neher</th>
<th>Clay</th>
<th>Hoerlin</th>
</tr>
</thead>
<tbody>
<tr>
<td>20°</td>
<td>10</td>
<td>1</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>3</td>
<td>3</td>
<td>0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>23°</td>
<td>10</td>
<td>3</td>
<td>4</td>
<td>-</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>7</td>
<td>10</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>50°</td>
<td>10</td>
<td>9</td>
<td>14</td>
<td>7</td>
<td>15</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>23</td>
<td>33</td>
<td>25</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

As Johnson says "At each latitude and elevation the agreement between the calculated and observed values is at least as good as that between the various observers. Therefore ..... it is concluded that within present accuracies of theories the positive component alone is sufficient to account for the entire variation of intensity with latitude." Of course, the experimental evidence upon which this conclusion is based is so far insufficient, and much more knowledge is needed, both of the
latitude-intensity changes, at various altitudes, and also of
the loss of energy of the corpuscular radiation in the atmosphere,
so the hypothesis of an exclusively positive primary radiation
awaits the test of future experimental work, before it can be
regarded as satisfactorily proved.

The Azimuthal Asymmetry.

Since the cones of possible directions for a particle of
given energy at a given latitude open up for positive particles
first from the west, and for negative particles from the east, an
azimuthal asymmetry means that unequal numbers of positive and
negative particles reach the earth at the given latitude. For
example, if measurements are made at $\theta^o$ to the vertical, the
particles coming from the west include all energies down to a
certain minimum $r_0$ for positives, and $r_0^{-1}$ for negatives, where
$r_0^{-1} > r_0$. The particles coming from the east include positive
energies down to $r_0^{-1}$ and negatives down to $r_0$. If there were
equal numbers of positives and negatives, with the same distribu-
tion of energy among them, the intensity would be symmetrical
about the vertical. Now although in 1931 Rossi looked in vain
for an azimuthal effect, it was discovered in 1933 by several
workers, T.H. Johnson, L. Alvarez and A.H. Compton, B. Rossi,
A. Ehrert, P. Auger and L. Lepirince Ringnet, and J. Clay. All
these experimenters find that the intensity from the west is
Fig. 52

Number of linear triple coincidences per hour.

- Observed at 35° S (Cuones Ayres).
- Observed on the geomagnetic equator.

West - Angle with vertical - East
greater than that from the east.

Fig. 14 is taken from a paper by Auger and Ringnet. It shows clearly that

1. There are more rays from the vertical at 38° S than on the magnetic equator, due to low energy rays which cannot enter at the equator, but come in at higher latitudes and are of sufficient energy to penetrate the atmosphere.

2. The western intensity at equator exceeds the eastern intensity, especially between 30° and 45° to the vertical; the ordinates at 30° and 45° have been drawn in to bring out this point.

The ratio of west to east intensity has been calculated by Johnson, as follows:

Using a similar notation to that used in calculating the latitude effect, let the fractional intensity of the total in a direction θ° E, due to positive rays of energy between r and r+dr, be \( f_+ \int J_+^1 \, dr \). Now the difference in east and west intensities due to positives only, is due to the inclusion at θ° W of lower energies than the minimum allowed at θ° E, down to the minimum energy at θ° W. Similarly for negatives, the difference in east and west intensities is due to the inclusion of the extra range of low energies permitted at θ° E in addition to those permitted at θ° W, and we must integrate for positives
Fig 53.

Curves calculated lines - data without absorber circles - with crosses - of Alvarez

Intensity ratios \( \frac{J_\theta}{J_\phi} \) vs. zenith angles for different locations.
and negatives over this range of low energies, and subtract the two results to find the total fractional difference

$$\frac{J_E - J_W}{J_E} = \int_{-\infty}^{\infty} \frac{r_0(\theta_E)}{r_0(\theta_N)} f_+ J_+^1 \, dr - \int_{-\infty}^{\infty} \frac{r_0(\theta_N)}{r_0(\theta_E)} f_- J_-^1 \, dr.$$  

Johnson has shown that if the second term is neglected, that is, the primary radiation assumed exclusively positive, and if

$$J_+^1 f_+^1 = 4e - 0.167 \sec \theta$$

then the calculated values agree remarkably closely with his observations. Fig. 16 (taken from Johnson's paper, Phys. Rev. 45, 569, 1934) shows curves which represent the calculated values for the ratio of the west to east intensity, at three different latitudes and three elevations. The points marked show the measured values. The biggest discrepancy occurs for a depth in the atmosphere of 6 metres, ($\varphi = 45^\circ$) in Peru.

We should expect

$$\frac{J_E - J_W}{J_E} = 100 \int_{-\infty}^{\infty} \frac{r_0 = 0.65}{r_0 = 0.43} 4e - 6 \times 0.167 \sec \theta \, dr$$

$$= 22\%.$$  

The observed value is $15\%$. However, most of the points are much closer to the curves than this, and Johnson's work, so far as it goes, is a brilliant confirmation of the theory. It is also
possible to calculate from the empirical expression

\[ J' = 4e^{-0.167z \sec \theta} \]

(which represents the intensity due to changed corpuscular rays per unit range of \( r \), expressed as a fraction of the total zenith intensity at the equator) the mean absorption coefficient of the corpuscular radiation. The mean absorption coefficient of the total radiation can be obtained by analysing a curve of Bowen, Millikan and Neher measured on the geomagnetic equator at depths 6 - 7 metres of water below the top of the atmosphere. It turns out to be 0.35 per metre of water, and we may write

\[ \text{Zenith intensity of the corpuscular radiation} = 4e^{-0.167z} \]

Thus the absorption coefficient of the corpuscular component is \((0.167 + 0.35)\) per metre water, a value which is in good agreement with the estimates of the absorption coefficient of the intense soft radiation found by analyses of the atmospheric absorption curve e.g. Eckart 0.6 m\(^{-1}\) water; Millikan 0.05 m\(^{-1}\) water; Regener-Lenz 0.49 m\(^{-1}\) water. Therefore according to Johnson's work, the soft component giving rise to most of the observed ionisation in the atmosphere is a corpuscular radiation; this was also the conclusion at which A.H. Compton arrived after the analysis of his curve, but Johnson's work goes further and shows the corpuscular radiation is positively charged.
The Transition Effect.

By "transition effect" is meant the abnormal absorption which occurs in the first few centimetres of a second medium following absorption in some other medium. The phenomenon was discovered by Hoffmann in 1927 and has been investigated very fully by Steinke and by Schindler. The latter have devised a "differential" apparatus, consisting of two ionisation chambers side by side, the currents from which are each taken to the same electrometer and made to nullify each other. Thus any deflection of the electrometer is due either to fluctuations in the ionisation process itself in each chamber, or to different screening above the chamber; external variations in the intensity are not recorded, since they occur simultaneously in both chambers. If the absorbing screens above the two chambers differ in thickness, then a current is measured which is the difference between the two total ionisation currents, and represents the difference in the ionisation due to the extra depth of absorber above one chamber. In this way absorption curves for several media were plotted (principal curves) and in addition transition curves were obtained, and the following facts discovered.

1. That if the ionisation is plotted as a function of the number of extra-nuclear electrons per square centimetre of the
Fig 54. Transition Curves between iron and lead

Ordinates a measure of the absorbed radiation
Abscissa = \( d = \frac{\rho Z d}{A} \) where
- \( \rho \) = density of medium
- \( Z \) = atomic number
- \( A \) = atomic weight
- \( d \) = thickness

\( 3 \times 6.06 \times 10^{23} \) = no. of electrons per sq. cm.
absorber, different curves are obtained for each medium, the heavier elements being the more effective absorbers. Recently it has been shown by Steinke and Tielack, that if the intensity is plotted as a function of the mass per square centimetre, the curves diverge even more. The mass per square centimetre is proportional to the total number of electrons per square centimetre, i.e. both extra-nuclear and nuclear electrons, so that it must be concluded that the absorption is not brought about by the electrons per se; the usual scattering of radiation by electrons cannot be the principal means of absorption.

2. The commencement of an absorption curve shows another feature - the first few centimetres of iron, lead and mercury instead of bringing about decrease in the ionisation, cause an increase which shows itself as a little hump at the beginning of the curve. (See Fig. 54)

3. The absorption after the initial increase, takes place at a greater rate in the next few centimetres than subsequently at great depths in the absorber.

4. At a transition from one medium to another, the curve leaves the "principal curve" of the first medium, and after a few centimetres of the second medium, reaches its principal curve. If the intensity at great depths in medium 2 is less than in equivalent depths of medium 1, then there is a rise of the ionisation
at a transition, and a subsequent rapid fall. Thus the humps observed in the principal curves of iron, lead, and mercury, are really due to a transition from air to one of these metals, in any of which the equilibrium intensity is less than in air.

The transition effect can be partly explained by making the assumption that only the secondary radiation produced in a medium gives rise to ionisation, and that the ratio of secondary radiation to primary is different for different media. Johnson has been able to calculate in this way the intensity in lead after a transition from air to lead, and obtains figures which agree closely with the measured values. In making the calculation, Johnson chooses suitable values for certain constants, such as the absorption coefficients of primary and secondary radiation in the two media, but he finds that there is disagreement between the number of secondaries produced per square centimetre per second in air as calculated from the constants chosen, and as measured by him in coincidence experiments with Geiger-Müller tubes. The values are 0.018 (calculated) and 0.0073 (measured). At the time of the calculation, the simultaneous production of two or more secondaries was just beginning to be observed, and Johnson accounts for the discrepancy by noting that only one of the simultaneous secondaries is sufficient to produce a coincidence.
Calculated Shower Curves (Bhabha)

Fig 55

I
Equilibrium intensity of secondary greater in air than lead

II
Less
The transition curves, explained in this way, bear many resemblances to the shower curves of Rossi, Fünfer, and Gilbert, (number of showers arising from a slab of lead plotted as a function of the thickness of the lead). The explanation of the initial increase of number of showers with screen thickness, the subsequent rapid decrease, and the final slow decrease has been explained quantitatively by Gilbert and by Bhabha. Each assumes that the showers are produced by a secondary radiation, the equilibrium intensity of which is different for different media. Bhabha's theory leads to one of two shower curves (see Fig. 55); the first is obtained if the equilibrium intensity of the secondary is greater in air than in lead, and the other for the reverse case. Both types of curves are found in the transition curves, but so far only the former type have been observed for showers.

Recent experiments of Street and Young bring out further points which indicate that the transition effect is due to the production of showers in a medium. They have obtained transition curves from air to lead at different altitudes and magnetic latitudes, using a spherical ionisation chamber of volume 230 ccs, filled with argon at 50 atmospheres pressure. Above it are placed lead discs subtending an angle of 41° at the centre of the chamber. Fig. 56 shows the curves obtained. A glance at them
Fig 56  Transition Curves XIX-lead

Thickness of upper lead shield in cms.

a  Lima  barometer 76  Hg  lat 1° S
b  Cambridge  76  52° N
c  Huancayo  51.3  1° S
d  Cerra da Pascia  45  1° S
shows the transition effect is much greater at high than at low altitudes. Table 5 shows the equilibrium ionisation for air and for lead, the latter obtained by producing backwards the flat part of the lead absorption curves (using for this extrapolation an absorption coefficient of 0.0064 per cm. lead). The difference of the two equilibrium intensities is a measure of the transition effect.

TABLE 5

<table>
<thead>
<tr>
<th>Place</th>
<th>Magnetic Latitude</th>
<th>Barometer in mercury</th>
<th>Equilibrium intensity in air (ions per cm/sec)</th>
<th>Equilibrium intensity in lead (ions per cm/sec)</th>
<th>Difference in transition effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cambridge</td>
<td>53° N</td>
<td>76</td>
<td>1.78</td>
<td>1.14</td>
<td>0.64</td>
</tr>
<tr>
<td>Lima</td>
<td>1° S</td>
<td>76</td>
<td>1.53</td>
<td>0.93</td>
<td>0.65</td>
</tr>
<tr>
<td>Huancayo</td>
<td>1° S</td>
<td>51.3</td>
<td>4.27</td>
<td>1.77</td>
<td>2.50</td>
</tr>
<tr>
<td>Cerro de Pasco</td>
<td>1° S</td>
<td>45</td>
<td>6.85</td>
<td>2.09</td>
<td>4.76</td>
</tr>
</tbody>
</table>

The ratio of the transition effects at Cerro de Pasco and at Lima is 8.7 : 1 (Street also reports a similar increase in the number of "Stösse"). This may be compared with the ratio 6.9 : 1 of numbers of showers observed by Johnson at sea level and at an altitude approximately that of Cerro de Pasco, and is a further indication that the transition effect is due to the production of showers. The table shows that the transition effect increases
much more rapidly with altitude than the equilibrium ionisation under lead. This suggests, as is pointed out by Street and Young, that the rapid increase of ionisation with altitude observed in Stratosphere flights, and the apparent softening of the radiation, may be due to a transition effect rather than to a true soft primary component. Another point brought out by the results, is that the magnetically deviable rays show the same transition effect as the total ionisation. If the ionisations measured at Lima (1° S) for shields 0 and 6.6 cms thick, are subtracted from the corresponding ionisations at Cambridge (53° N) the difference is due to those charged corpuscles which fail to reach the equator because of the earth's magnetic field.

<table>
<thead>
<tr>
<th></th>
<th>Ionisation with no shield</th>
<th>Ionisation under 6.6 cms lead</th>
<th>Ratio shielded/unshielded</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cambridge 53° N</td>
<td>2.48</td>
<td>1.84</td>
<td>.74</td>
</tr>
<tr>
<td>Lima 0° S</td>
<td>2.14</td>
<td>1.59</td>
<td>.70</td>
</tr>
<tr>
<td>Difference</td>
<td>0.34</td>
<td>0.25</td>
<td>.73</td>
</tr>
</tbody>
</table>

It seems that the particles which we know must be charged, (because they produce the latitude effect,) are absorbed in the same way as the total ionisation, and putting together the facts already known about showers, transition effect, and the charged
part of the radiation, we have strong evidence for supposing that the incident radiation is a corpuscular radiation, positively charged (since the experiments on the magnetically deflectable rays show them to be positively charged, and there is no reason for supposing them to be different from the others) and absorbed in air and other media chiefly by the production of a radiation which in its turn produces the showers.
Fluctuations in the Intensity of Cosmic Radiation.

Barometer Effect.

In 1925 Myssowski and Tuwin discovered that the intensity of the cosmic radiation, measured with an ionisation chamber sunk to a depth of a metre in water, showed fluctuations which could be at once correlated with atmospheric pressure, in fact that the two curves showing ionisation and pressure as a function of time ran "spiegelbildlich" side by side. This could be at once explained, since the barometric pressure is a measure of the mass of air lying above a place, and hence the greater the pressure, the greater the equivalent thickness of the atmosphere considered as an absorbing medium. The "barometer effect" was defined as the percentage change in the intensity for a change of pressure of 1 m.m. mercury, and was found by Myssowski and Tuwin to be -0.7%. Since then many German workers have carried out long series of experiments on fluctuations in the apparent intensity of the cosmic radiation; it was soon discovered that other factors cause variations, such as atmospheric temperature, temperature of the measuring apparatus, fluctuations in the ionisation process itself. The problem has been investigated very fully by Hoffmann and his collaborators Steinke, Pforte, and Messerschmidt, at Halle, where they have set up two large ionisation chambers, of volume 24.5 litres, filled with carbon.
Fig 57

Barometer Effect for rays of different hardness

Fig 58

Effect of a Sudden Depression

Fig 59

Temperature Effect for radiation incident at different angles

1. Radiation incident at 55° to vertical
2. Radiation incident at 45° to vertical
3. Radiation incident at 25° to vertical
4. Vertical radiation

Abscissa - mean European time.
dioxide at 26 atmospheres pressure; the average current in each is "compensated", as already described, and therefore only variations in the radiation are recorded. Fig. 57 shows the results of continuous records lasting for many months. The numbers near the points give the number of measurements which have been taken to compute the average intensity for the pressure in question. There is greater scattering of the points in the case of the soft (unfiltered) radiation, which is more affected by other atmospheric conditions than the hard radiation, and the smooth curve drawn through the points is not a straight line. In the case of the filtered radiation, the barometer effect is much less, and the measured points do lie very close to a straight line. If the radiation were incident only in a vertical direction, one would expect a simple exponential curve, and as the changes in intensity are all small compared with the total intensity, the exponential approximates to a straight line. An absorption coefficient can be estimated from the ionisation pressure curve; a barometer effect of $-0.7\%$ corresponds to an absorption coefficient of $0.07 \text{ cm}^{-1}$ mercury. It was at first thought that the absorption coefficient calculated in this way should agree with that calculated from the difference in intensity measured at two places at different altitudes; however, an agreement only in order of magnitude can be expected, for the radiation
is not homogeneous, and it comes into the earth's atmosphere in all directions with equal intensity, the pressure recorded giving no information about the mass of air penetrated by the oblique rays. This accounts for Messerschmidt's discovery that changes in intensity due to very sudden pressure changes (depressions) lead to values for the barometer effect which are different from those measured for slow changes. Sudden depressions are very localised, and therefore only the rays incident at small angles to the vertical are affected by the change, not those coming in more obliquely. Figs. 58 taken from a paper by Messerschmidt and Pforte show measurements taken during such a sudden depression. When the pressure is falling the radiation at each pressure is less than would be expected from the average barometer effect, but a short time after the minimum of the depression the measured values begin to agree again with those calculated.

Changes due to temperature.

Messerschmidt showed that the ionisation current was influenced also by the outside temperature, a rise of temperature corresponding to a rise in the ionisation and vice versa. This was partly explained when he made the surprising discovery that if he allowed unfiltered radiation to enter his chamber in a horizontal direction only, (screens open at the side,) then the
Ionisation time curve is the inverse of the curve for vertical radiation, i.e. the ionisation due to horizontal radiation decreases as the temperature increases, and the amplitude of the change is much greater than for the vertical radiation (see Fig. 59) Messerschmidt's explanation is that the horizontal radiation is nearly all due to the presence of radium emanation in the air. When the temperature rises after sunrise, thermal convection carries the layer of air which is rich in emanation, higher, and the ionisation due to horizontal radiation therefore falls off. When the earth begins to cool (a little after midday) thermal convection ceases, and the layer of air near the earth accumulates radium emanation again, the products of which give rise to γ-rays which cause the ionisation due to radiation coming in directions near to the horizontal to increase. Messerschmidt questions whether the temperature variations of the radiation incident vertically are to be similarly explained, as he finds the temperature effect is still present in the filtered radiation. His result is confirmed by continuous measurements taken by V.F. Hess and R. Steinmaurer in 1932 and 1933 on the summit of Innsbruck, where a steel ionisation chamber, of 22.6 litres capacity, filled with carbon dioxide at 9.5 atmospheres, is set up; all ionisation values are reduced to the same barometric pressure and outdoor temperature, yet the
existence of a small diurnal variation was proved beyond doubt.
The maximum occurs at 2 p.m., indicating an indirect rather than
a direct solar influence, and it is not possible yet to give an
explanation which is open to no objections.

Effect of Magnetic Storms.

A. Corlin has found that at Abisko in North Sweden the
intensity increases after the beginning of a magnetic Storm;
Hess and Steinmaurer however report a slight decrease both in the
case of a completely screened chamber and a chamber unscreened at
the top. They agree with Corlin that it is quite possible that
a decrease in the intensity in Central Europe may be accompanied
by an increase at higher latitudes (Abisko 68°N), and future
records of both taken during the same magnetic disturbance will
show whether this is actually the case.

Effect of Sunspots.

O. Freytag has analysed the extensive observations of
Lindholm at Muottas Murzgl (Upper Engadine) and concluded that
the diurnal variation of the more penetrating components of
cosmic radiation is more marked in periods when relatively large
numbers of sunspots are observed. Hess and Steinmaurer cannot
report a certain correlation; Hess observes that "a slight
increase noticeable between ten and fifteen days after the passage
of large spots through the central meridian is still uncertain
and may be purely incidental. "In addition to these observations may be mentioned the fact that Regener points out that his stratospheric ionisation curve which showed the abnormally high intensity at the top of the atmosphere, was taken on a day when sunspots crossed the meridian.

**Other Periodic Variations.**

All investigators now agree that there is no correlation to be found between the intensity and sidereal time, and the important inference to be drawn from this fact is that the radiation comes into the earth's atmosphere with equal intensity from all directions in space. Experiments have not been continued for periods long enough to show yet any seasonal or annual variation; if present they are very small, and the difficulty of eliminating all other factors causing fluctuations has made it impossible to make any statement about them.

"Stösse".

In a short report (Physikalische Zeitschrift 31, p.347, 1930) of the record of cosmic radiation taken by Hoffmann & Lindholm at Nuottas Nuurigl, with the 50 litre ionisation chamber containing carbon dioxide at a pressure of 30 atmospheres, Hoffmann describes how in addition to small fluctuations of about ±1° there appear two or three times a day what he calls "Stösse", that is to say, the records show from time to time the electrometer fibre is deflected much more than is usual, and Hoffmann estimates that the
Fig. 60

Stösse from Aluminium

Most frequent
Minimum no. of ions

$2 \times 10^6$

Fig. 61

Stösse from lead

Most frequent
Maximum no. of ions

$3.8 \times 10^6$
size of the "kick" corresponds to the simultaneous arrival of several million ions at an electrode. He could find no instrumental fault to account for the Stosse and moreover discovered that they were never recorded in deep mines. In 1932 Steinke & Schindler (Zeits. für Physik 75, p.115, 1932) using the differential apparatus, found that the Stosse were more frequent when the chambers were shielded by 10 cms. of lead placed above them, than when they were unshielded. At the London Physics Conference in October 1934 Hoffmann presented new information obtained by Messerschmidt, as a result of shielding the ionisation chamber with screens of lead and aluminium of different thicknesses. The number of Stosse per hour from lead decreases as the thickness of the lead increases from 5 to 20 cms., but with aluminium the number increases up to 30 cms. shielding (See figs. 60 & 61). The maximum number of ions formed in a "burst" is characteristic of the element, and amounts to $3.3 \times 10^6$ for lead, $2.8 \times 10^6$ for aluminium.

A very short report was given at the Conference by A.H. Compton and R.D. Bennet, who have studied bursts at different altitudes. They find that the frequency of the bursts increases more rapidly with altitude than the intensity of the general cosmic radiation. They are able to classify the bursts into two groups, the larger group consisting of
bursts at sea level, and the smaller group bursts at high altitudes, which involve more ions than the sea level bursts - up to as many as $7 \times 10^9$ ions.

So far the cause of the Stosse is not known, but it is very natural to associate them with the showers observed in Wilson expansion chambers, in spite of the fact that they represent very many more ions than are observed in showers. Millikan, Anderson & Weber have suggested that they are caused by the setting in of ionisation by collision in the ionisation chamber. Since, however, W.F.G. Swann has obtained Stosse "with potential differences as low as 4.5 volts, which even with the aid and conspiracy of all known phenomena could not give rise to bursts of ions by ionisation by collisions" and Compton too finds them in an apparatus working at 13 volts, Millikan's explanation must be rejected. In any case it would be very difficult to account for the systematic results of Messerschmidt if the cause of the stösse were ionisation by collisions. As their frequency increases more rapidly with altitude than the general cosmic radiation, it seems that they may be associated with the corpuscular radiation of absorption coefficient about 0.5 per metre water, which is known to produce the showers; they would then be regarded as large and correspondingly infrequently occurring showers. As
Fig 62

Energy distribution of +ve and -ve electrons occurring singly in the chamber.

Fig 63

Energy distribution of +ve and -ve electrons occurring in showers in the chamber.
Wilson Expansion Chamber Photographs, and the Conclusions to be drawn from them.

Reference has already been made to the important discoveries made by workers with Wilson Expansion Chambers. The main facts that emerge at present are as follows:

1. That of all the single tracks appearing in the photographs (that is, excluding tracks in showers) rather more than half are positive. Fig. 62 shows their energy distribution curve, according to measurements of their curvature in a magnetic field by Anderson.

2. That showers of particles, of varying degrees of complexity, appear frequently in the photographs. As many as eighty particles have been observed in one shower, but the number is usually less. The total energy of all the particles occurring in a shower has never been found to be greater than $3 \times 10^9$ electron volts. There are about equal numbers of positive and negative electrons in the showers, and their energy distribution curve is given in Fig. 63. Most of the shower particles have an energy of about $10^7$ e.v. but some have ten times this energy.

3. The showers often appear to diverge from some point above the chamber, but often it is impossible to say whether they do arise from a common point or not. It has been noticed by Blackett and Cocchiaiini that when one shower occurs there is a
high probability that another will occur near to it, which suggests that the immediate cause of the showers is a non-ionising radiation.

4.

The loss of energy in lead has been measured by Anderson, by measuring the curvature of tracks before and after passing through a lead plate. Table 6 summarises these measurements.

**Table 6**

<table>
<thead>
<tr>
<th>Sign of Charge</th>
<th>Initial Energy m.e.v.</th>
<th>Specific energy loss m.e.v./cm.</th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td>115</td>
<td>20</td>
</tr>
<tr>
<td>-</td>
<td>240</td>
<td>18</td>
</tr>
<tr>
<td>-</td>
<td>220</td>
<td>55</td>
</tr>
<tr>
<td>+</td>
<td>33</td>
<td>29</td>
</tr>
<tr>
<td>+</td>
<td>63</td>
<td>57</td>
</tr>
<tr>
<td>+</td>
<td>200</td>
<td>63</td>
</tr>
<tr>
<td>+</td>
<td>140</td>
<td>120</td>
</tr>
<tr>
<td>-</td>
<td>105</td>
<td>80</td>
</tr>
<tr>
<td>-</td>
<td>110</td>
<td>65</td>
</tr>
</tbody>
</table>

It is difficult to compare these experimental values with any
theoretical values, because of the large fluctuations in the figures for the energy loss per centimetre. However, Bethe and Heitler have recently published a table giving the results of their calculations for energy loss due to radiative collisions (i.e. collisions resulting in the emission of a γ ray) in lead. Their figures are 14.4, 177, and 1900 million electron volts per cm. for electrons of energy 10, 100 and 1000 million electron volts. These are much higher than the values measured directly by Anderson, and in this respect theory and experiment do not agree. However, it is very likely that the theory will be modified by taking into account other factors at present ignored.

With regard to the production of showers by photon radiation, Blackett and Occhialini have drawn attention to the Dirac theory of the electron, which shows that when high energy γ rays are absorbed in matter, a pair of electrons of equal mass but opposite sign may be produced. The total kinetic energy $E$ of the pair is given by

$$E = h\nu - 2mc^2$$

where $h\nu$ represents the energy of the γ ray quantum, $m$ is the mass of each electron, and $c$ is the velocity of light in empty space. This is an immediate consequence of the fact that the production of each electron requires the expenditure of $mc^2$ energy unit. This is borne out very well by experiments of
Anderson with γ rays of energy \(2.6 \times 10^6\) electron volts. Of the 22 pairs examined, only one had a total kinetic energy greater than \(1.6 \times 10^6\) e.v., and of the single positive electrons measured (which seem to have acquired all the kinetic energy after the collision) not one had energy greater than \(1.6 \times 10^6\) e.v., leaving in each case \(10^6\) e.v. (= 2 mc²) for the energy used in the production of the pair. The area of cross section of a lead atom for the production of positrons has been found by Blackett, Chadwick and Occhialini to be \(2.8 \times 10^{-24}\) square centimetres. Heitler and Sauter have calculated the value \(2.6 \times 10^{-24}\), Oppenheimer and Plesset, \(3.9 \times 10^{-24}\). These values are greater than the cross section of the lead nucleus, showing that the positrons originate in the electric field outside the nucleus.

It is interesting to compare these values with the cross section obtained by Gilbert for the production of showers in lead. Since he finds the absorption coefficient of the shower producing radiation is 0.33 per centimetre, it follows that the area of cross section for the production of a shower is \(11.4 \times 10^{-24}\) sq. cms., which is of the same order as those observed and calculated for the production of electron pairs. Moreover Gilbert finds that the cross section is roughly proportional to the square of the atomic number of the absorbing element, and Oppenheimer and Plesset have shown that the cross section for electron pair production, \(\sigma\), is
Where $Z$ is the atomic number of the element, and $e$, $m$ and $c$ have their usual significance. Thus there is every reason for supposing that showers are due to the simultaneous production of several electron pairs by \( \gamma \) radiation in the field outside the nucleus.

\[
\sigma \sim \frac{2^2}{137} \frac{e^4}{m^2 c^4}
\]
Conclusion.

Although the chief problems of cosmic radiation, namely, its nature and origin, are still unsolved, yet the important discoveries of the last few years have made possible the following statements.

1. Cosmic radiation comes into the earth's atmosphere with equal intensity from all directions in space.

2. It consists at least in part of charged particles; there is evidence for believing them to be of two kinds, since Rossi finds that rays which penetrate 8 cms lead show a greater azimuthal asymmetry than the unfiltered corpuscles, and analyses of the ionisation depth data is not inconsistent with the view that the less penetrating corpuscles are electrons, (possibly positive only,) while the more penetrating corpuscles are protons.

3. In addition to these components which are magnetically deflectable and therefore charged, measurements at great depths in water and in mines have shown some components with a range as great as 250 metres and 500 metres of water respectively, and stratosphere flights indicate the presence of a very soft component which is absorbed in the first metre or two (equivalent metres of water) of the atmosphere. Further experiments are needed to decide whether these components are charged or not.
4. The greater part of the ionisation at sea level is due to about equal numbers of positive and negative secondary rays, which are probably shower particles owing their origin to the primary electrons.

As to the origin of the primary radiation, nothing has been said in the present paper, because such enquiries can only be very hypothetical until the nature of the rays is known more certainly, and this will only be revealed when more is known about the absorption of high energy corpuscles and photons in matter.