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Cosmic-Ray Ionization at High Altitudes

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A criterion for the nature of cosmic rays. Cosmic rays may be interpreted as photons only if at all altitudes $d^2(\log \psi)/dP^2>0$, where P is the barometric pressure and ψ is the intensity as a function of the pressure for rays descending vertically through the atmosphere. Gross has shown how ψ can be determined directly from the observed intensity I, due to rays from all directions. The rays may be interpreted as ionizing particles with a definite range ("r-particles") only if the relation $d^2I/dP^2>0$ is satisfied. Measurements by a recording cosmic-ray meter, with walls equivalent to 6 cm of lead to avoid transition effects, were made on the recent Settle-Fordney stratosphere balloon flight. Through the altitude range from 40 to 15 cm Hg the ionization-pressure relation satisfies the criterion for r-particles but not that for photons. This result is confirmed by comparison with other high altitude data.

Ionization of primary cosmic rays as function of altitude. The measurements when graphically analyzed show the presence of rays of two distinct range groups, A and B. Group B has ranges greater but apparently not less than the air equivalent of 27 cm Hg, with a strong maximum at 36 cm. This group is ascribed to electrically charged rays which require energies greater than that corresponding to 27 cm range in order to penetrate the earth's magnetic field. Protons and possibly positrons meet these requirements, but not α-particles nor heavier nuclei. Group A is most prominent at the shorter ranges, and shows no maximum for ranges greater than 10 cm Hg. It thus represents rays unaffected by the earth's magnetic field, and hence neutral or with a ratio of mass to charge equal to or greater than that of an alpha-particle. Apparently range group A is almost completely confined to the upper atmosphere.

Photons cannot constitute more than a negligible part of primary cosmic rays. Comparison of high altitude measurements at the equator with those at high latitudes shows that the equatorial cosmic rays are closely similar to the magnetically deviable rays both in their absorption in air and in their transition effects. This indicates that most of the cosmic rays which reach the earth are similar in character to the deviable rays, most probably protons. Any primary cosmic photons which may reach the earth apparently produce an imperceptible effect.

1. A Criterion for the Nature of Cosmic Rays

It is well known, from the studies of Kolhörster, Regener and others, that the ionization due to cosmic rays increases rapidly with increasing altitude, but that near the top of the atmosphere the rate of increase diminishes. This change in shape of the ionization curve at high altitudes is usually ascribed to a transition effect, due to the secondary rays produced as the primary cosmic rays enter the atmosphere. Only below such a depth that the secondary rays are in constant ratio to the primary rays does the observed ionization serve as a measure of the intensity of the primary cosmic rays. It is possible however to eliminate this transition effect by using an ionization chamber whose walls are so thick that all of the secondary rays from the air are absorbed, and the rays which reach the inside of the chamber are in equilibrium with the secondaries from the chamber walls. The observed ionization in such a chamber should be proportional to the intensity of the primary rays all the way to the top of the atmosphere. We have recently measured the cosmic rays up to high altitudes using a thick-walled ionization chamber in which this condition is approximately realized.

If the ionization is thus proportional to the intensity of the primary rays, the relation between the ionization and the depth below the surface of the atmosphere may be of such a form that it can be described in terms of ionizing particles but not in terms of photons. Let us determine the criterion for this distinction.

For this purpose we shall define *r-particles* as particles with a definite range, and ionizing the absorbing matter uniformly throughout that range. Alpha-rays, beta-rays, protons and positrons would fall approximately into this classifi-

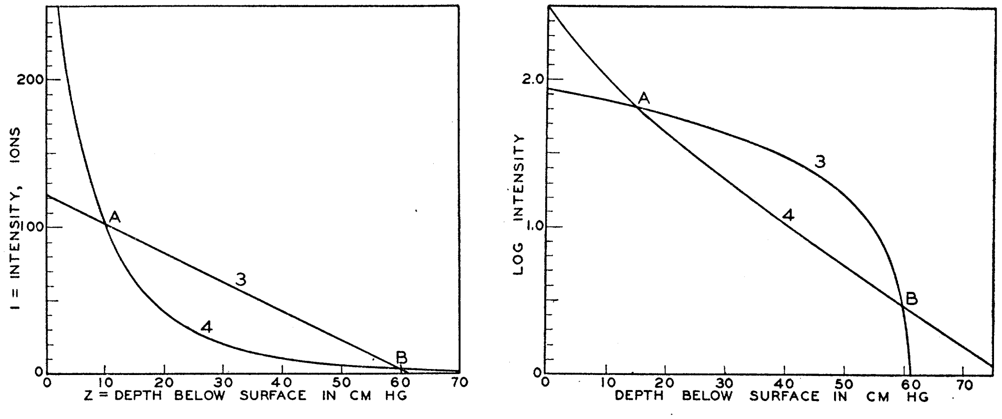

FIG. 1. FIG. 2.

FIGS. 1 AND 2. Calculated ionization by isotropic cosmic rays, *3* by ionizing particles with a definite range, *4* by homogeneous photons.

cation. We shall assume also that a photon traverses matter without loss of energy until in one cataclysmic event it loses a large part or all of its energy. The ionization due to a homogeneous beam of *r-rays* traversing an absorbing medium parallel to the Z axis is thus,

$$I_r = I_0 \quad [z<r]$$
$$= 0, \quad [z>r], \tag{1}$$

where I_0 is the ionization at the surface of the medium and r is the range of each particle. The ionization due to a homogeneous beam of photons is,

$$I_p = I_0 \exp(-\mu z), \tag{2}$$

where μ is its constant absorption coefficient.

Assuming that the cosmic rays enter the atmosphere as r-rays, uniformly from all directions, a simple integration shows that a fraction $(r-z)/r$ will penetrate to a depth z. Thus the ionization at a depth z below the surface of the atmosphere, due to homogeneous, isotropic r-rays coming from outside, should be,

$$I_r = I_0(r-z)/r. \tag{3}$$

The corresponding expression for the ionization at a depth z below the surface of the atmosphere, due to homogeneous, isotropic photons coming from outside has been shown by Millikan and Cameron[1] to be,

$$I_p = I_0 G(\mu z), \tag{4}$$

where[2]

$$G(\mu z) = 2\pi \int_0^\infty z^{-2} \exp(-\mu z x) dx. \tag{5}$$

In Figs. 1 and 2 the intensity and the logarithm of the intensity are plotted respectively against the depth z, according to expressions 3 and 4. Points A and B represent experimental values at two levels in the atmosphere. Curve 4 represents a beam of homogeneous photons. If more than one component is present, the curve becomes more strongly concave upward. Thus if an experimental ionization curve is straighter than No. 4, or is curved downward, it cannot be due to photons (except for the effect of secondary rays, as will be discussed below). The straight line of Fig. 1 represents homogeneous r-rays. If groups of r-rays of different ranges are present, it is clear that an ionization curve such as 4 might result. If we let $I = f(z)$ be the ionization depth relation, it can in fact be shown, using Eq. (3), that the number of r-particles entering the top of the atmosphere with ranges between z and $z+dr$ is[3]

$$R(r)dr = z(d^2I/dz^2)dr. \tag{6}$$

Since R must be positive to have physical significance, this means that r-rays can produce

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[1] R. A. Millikan and G. H. Cameron, Phys. Rev. **28**, 860 (1926).

[2] E. Gold, Proc. Roy. Soc. **A82**, 62 (1908) gives a table of this integral for various values of (μz).

[3] This relation has been given by B. Gross, Zeits. f. Physik **83**, 217 (1933).

any curve which has at all points an upward curvature, i.e., for which

$$d^2I/dz^2>0. \qquad (7)$$

It follows that any ionization *vs.* pressure relation which can be accounted for by photons can also be accounted for in terms of ionizing particles with a definite range. On the contrary, curves lying between 3 and 4 can be represented by particles with a definite range (*r*-rays) but not by photons.

2. Experimental Requirements

The experimental data taken in the air at moderately high altitudes will be shown to follow curves intermediate between 3 and 4. As we have seen, this can be taken as definite evidence against their photon nature only if the ionization chamber is surrounded with a wall sufficiently thick to absorb the secondaries produced in the air, in which case the ionization by homogeneous photons should be proportional to the energy per unit area of the incident beam.

The wall thickness necessary to absorb the secondaries from air may be found from observations of transition effects. Those measured by Schindler[4] at approximately sea level are detectable through about 10 cm of lead. We have performed similar experiments[5] on Mt. Evans (4300 meters). There the "soft component," which constitutes only about 16 percent at sea level, forms about 60 percent of the cosmic rays. Fig. 3 shows the ionization as observed for lead shields of different thickness completely surrounding the chamber. The curve is similar to those given by Schindler, but shows that the transition effects are appreciable to only about 7 cm of lead.[6] This difference presumably corresponds to the higher absorption of the soft rays at this high altitude.

3. The Measurements

A cosmic-ray meter with heavy walls was accordingly carried by Commander T. G. W. Settle and Major C. L. Fordney on their stratosphere balloon flight,[7] on November 20, 1933. The ionization chamber was argon filled, and was surrounded by 9.6 cm of fine lead shot, contained in a hollow sphere of wood, equivalent to about 5.8 cm of solid lead. The 0.3 cm steel wall of the chamber, equivalent to 0.2 cm of lead, made the effective wall thickness equivalent to 6.0 cm of lead. It will be seen from Fig. 3 that this thickness is sufficient to absorb almost completely the secondary rays which are responsible for transition effects. The meter was one of those[8] used on our geographic survey of cosmic rays, fitted however with a recording camera. The argon pressure was reduced to 2.4 atmospheres, insuring saturation with 180 volts across the chamber even for the intense rays near the top of the atmosphere.

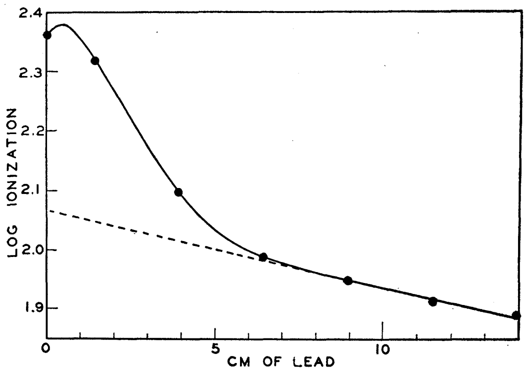

Fig. 3. Transition effect in lead at altitude of 4300 meters.

The motion of the Lindemann electrometer needle was photographed on a standard 35 mm film, moving about 2.5 mm per minute. The needle was automatically returned to a suitable

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[4] H. Schindler, Zeits. f. Physik **72**, 650 (1931).

[5] These observations were made by J. C. Stearns in 1931, using the apparatus described by R. D. Bennett, J. C. Stearns and A. H. Compton, Phys. Rev. **41**, 119 (1932). The shield nearest the ionization chamber was copper.

[6] This shorter average range at high altitudes of the secondaries which produce the transition effect has previously been noted by L. M. Mott-Smith and L. G. Howell, Phys. Rev. **44**, 8 (1933), from their airplane measurements. Their data agree closely with those here given.

[7] Cf. A. H. Compton, Proc. Nat. Acad. Sci. **20**, 79 (1934), for account of the scientific observations on this flight.

[8] For description, cf. A. H. Compton and J. J. Hopfield, Rev. Sci. Inst. **4**, 491 (1933).

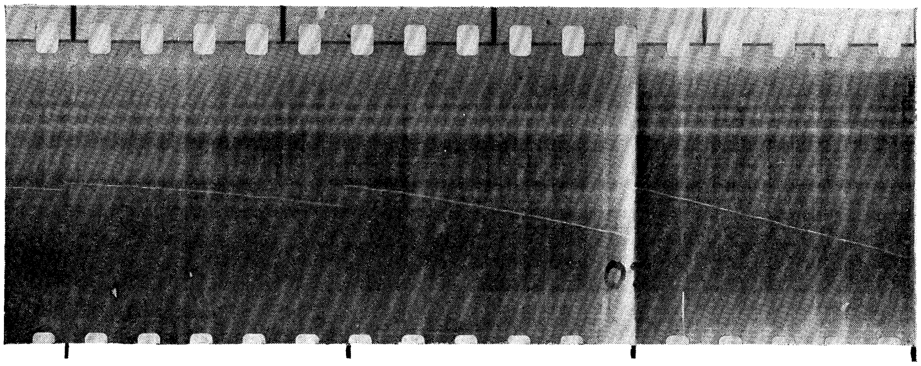

FIG. 4. Trace of shadow of electrometer needle during period of rapid ascension into stratosphere.

initial voltage at successive 10 minute intervals, and once each hour was charged to a known potential for calibration (Fig. 4).

The barometric pressure was determined (1) by direct reading of a double U-tube barometer,[9] and (2) from the record of a barograph placed outside of the gondola.[10] The times and pressures recorded by the observer in his direct reading of the barometer were used as standards, and the barograph record was used only to interpolate between the direct barometer readings. The values of the barometric pressure are probably correct to 1 mm, while the time scales of the barometer and the cosmic-ray record may differ by 1 or 2 minutes.

In Fig. 5, data thus obtained are shown both in the form of a graph of the individual determinations, and of a table showing the mean values. The small solid circles represent the values observed as the balloon ascended. These values are averages over a period of 10 minutes each, except those between 40 cm and 12 cm, which were averaged for 5 periods of one minute each because of the rapid rise of the balloon, and the point at 73.5 cm, which is the average of 2 hours of readings on the ground immediately before the flight. The small open circles show the ionization measured as the balloon descended. When the balloon had descended to a pressure of about 16 cm, the lead shot composing the shield were thrown out as ballast, and no further record was made.

For standardizing the readings, the ionization due to the cosmic rays at ground level (73.5 cm Hg) was taken as 1.81 ions per cm^3 per sec. in standard air, a mean value of many measurements made with similar meters. There was also a correction for "wall radiation" from the chamber itself of 0.85 standard ions, as shown by measurements made with the chamber in a deep mine.

4. COMPARISON WITH OTHER MEASUREMENTS

Though we find no record of previous measurements with heavy walled chambers at heights comparable with those here attained, studies made on mountains and in airplanes give valuable comparison data. Of the mountain observations, those most directly comparable are the ones recently made by our associated expeditions using instruments essentially the same as the present one. The large open circles shown in Fig. 5 are taken from the curves[11] representing these data on mountains at about the magnetic latitude at which this balloon flight was made, corrected however for a wall radiation of 0.13 ions, which had not been applied to the published mountain data. Our method of standardization makes the balloon datum for 73.5 cm agree with

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[9] This barometer was designed and built under the direction of Professor A. Piccard.

[10] We wish to thank Dr. W. G. Brombacher of the Bureau of Standards for furnishing a copy of this record and the result of his analysis for determining the official height (18,665 meters) attained by the balloon.

[11] A. H. Compton, Phys. Rev. **43**, 396 (1933) Figs. 5 and 6.

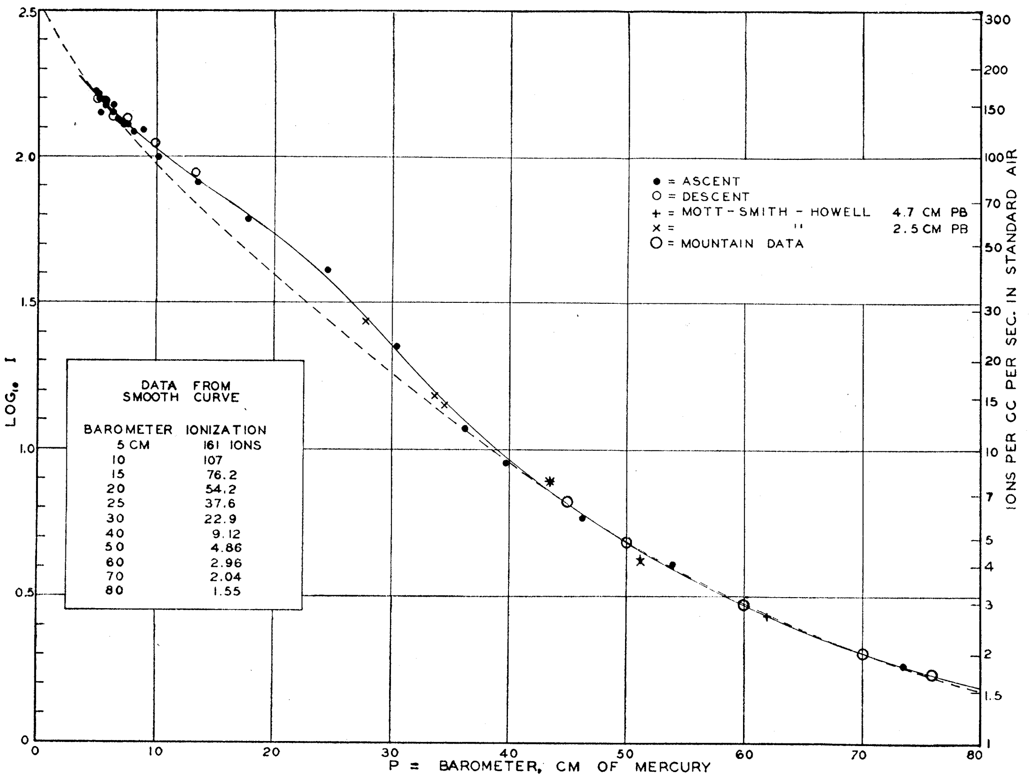

FIG. 5. Ionization as function of atmospheric pressure (altitude) in chamber with walls equivalent to 6.0 cm lead.

our value measured on the ground. The excellent agreement of the balloon data at 54 cm and 46.2 cm with the precision mountain values indicates, however, the reliability of the measurements made in the balloon.

Mott-Smith and Howell[12] have also published data taken with a heavy-walled ionization chamber carried to a high altitude in an airplane by Captain A. W. Stevens. The crosses of Fig. 5 show their data when using a chamber with 1.3 cm steel walls surrounded by 4.7 cm lead shields. Their data are multiplied by such a factor as to bring their lowest recorded datum (at 62 cm) onto our curve. At barometric pressures less than 43.5 cm, the heaviest shield used in Mott-Smith and Howell's experiments was 2.5 cm of lead. Their values thus measured for pressures below 52 cm are here represented by ×'s. These values are adjusted to fall on their datum when using the 4.7 cm shield for the 43.5 cm point. Mott-Smith and Howell's experiments thus supply an independent set of data between 62 and 28 cm that is closely comparable with our own. The agreement is highly satisfactory.

A major feature of the data shown in Fig. 5 is the marked hump in the curve at about 25 cm pressure. The only previous data taken at altitudes sufficient to show this hump clearly are those which have been obtained in balloons by using thin walled chambers. To compare our measurements with those using thin walled chambers we may apply to all the measurements Gross's transformation,[13]

$$\psi = I - P dI/dP, \tag{8}$$

where ψ is the intensity at a barometric pressure P supposing that the radiation enters normally

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[12] L. M. Mott-Smith and L. G. Howell, Phys. Rev. **44**, 4 (1933).

[13] B. Gross, reference 3, p. 216. This procedure seems to be rigorous if the cosmic rays are photons, but is questionable if they are of the r-type.

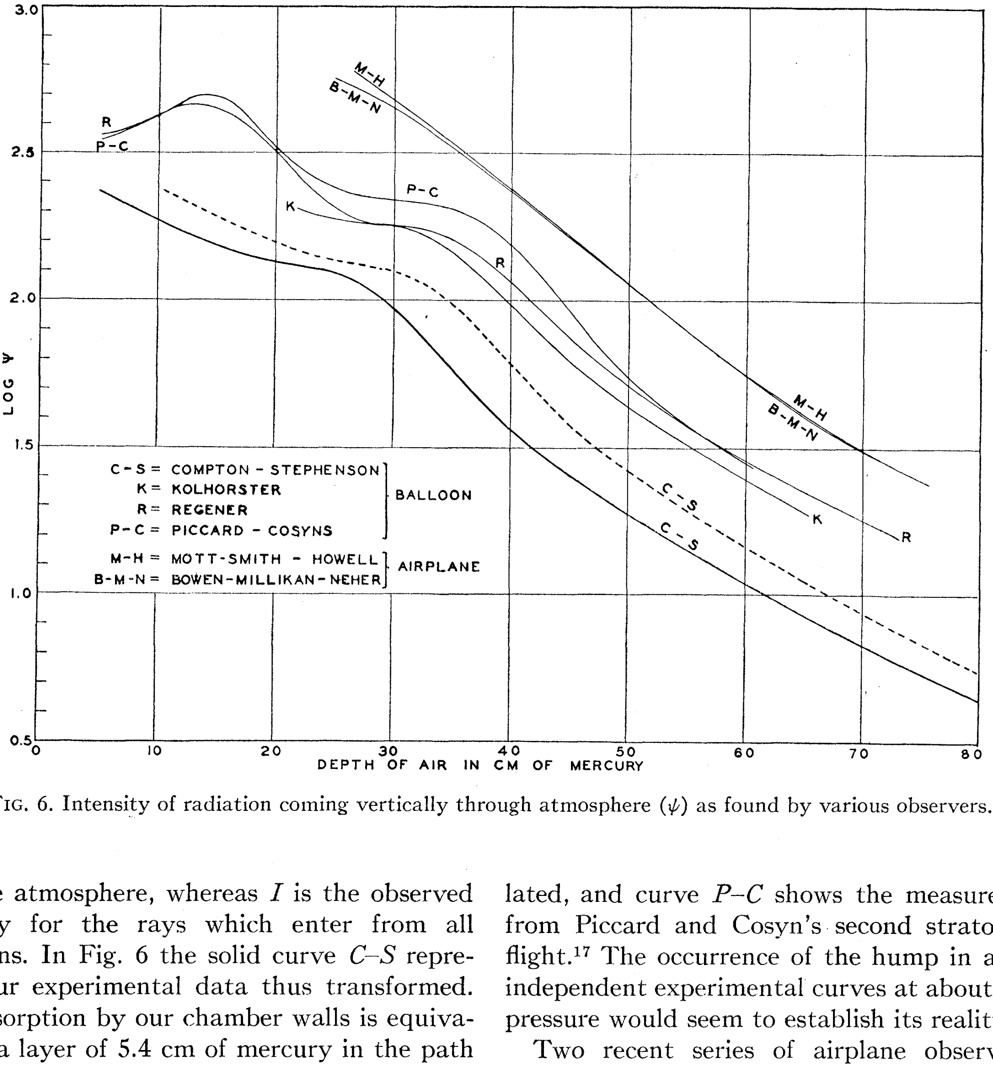

FIG. 6. Intensity of radiation coming vertically through atmosphere (ψ) as found by various observers.

into the atmosphere, whereas I is the observed intensity for the rays which enter from all directions. In Fig. 6 the solid curve *C–S* represents our experimental data thus transformed. The absorption by our chamber walls is equivalent to a layer of 5.4 cm of mercury in the path of a parallel beam of cosmic rays,[14] so in the dotted line *C–S* we have plotted the same data for a pressure $P+5.4$. This should be comparable with data obtained from an unshielded chamber after transformation by Eq. (8).

Curve *R* of this figure is a logarithmic plot of Regener's sounding balloon data as similarly transformed by Gross.[15] Curve *K* represents Kolhörster's early balloon data[16] similarly calculated, and curve *P–C* shows the measurements from Piccard and Cosyn's second stratosphere flight.[17] The occurrence of the hump in all four independent experimental curves at about 35 cm pressure would seem to establish its reality.

Two recent series of airplane observations have a somewhat different shape. Curve M–H of Fig. 6 represents the data thus transformed got by Mott-Smith and Howell with no lead shield,[18] and curve B–M–N is that of Bowen, Millikan and Neher[19] at geomagnetic latitude 42°N. All the other curves in this figure represent

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[14] 6 cm of lead is equivalent in mass to 5 cm of mercury. A calculation by C. Eckart shows that for our case the absorption by a 5 cm spherical wall is equivalent to that by a 5.4 cm plate placed normally to the beam.

[15] B. Gross, reference 3, p. 218.

[16] Data taken from Hess, *Electrical Conductivity of the Atmosphere* (1928), p. 133, with $I_0=3$ ions.

[17] A. Piccard and M. Cosyns, C. R. **195**, 605 (1932). Curve *P* of Fig. 6 is based not on the curve given in their paper, which falls markedly below their datum at 34 cm, but upon a smooth curve averaging all of their experimental points.

[18] Mott-Smith and Howell, reference 12. Data taken from their average curve.

[19] I. S. Bowen, R. A. Millikan and H. V. Neher, Phys. Rev. **44**, 248 (1933). Data taken from their smooth curve in Fig. 2.

data from about 51°N geomagnetic latitude. (Curves M–H and B–M–N are shifted upward by a factor of $10^{\frac{1}{2}}$ to avoid overlapping.) These curves give only a slight indication of a hump at 30 cm pressure, though both show an extended portion which is slightly concave downward. The airplane flights were not sufficiently high to extend the cosmic-ray measurements beyond the hump. This probably accounts for the failure of these data to reveal the presence of the hump more clearly.

5. Significance of the Data

A very remarkable fact shown by the data given in Fig. 5 is that over the range from 10 to 40 cm of mercury the log I *vs.* P curve is concave downward. This, as our discussion of Fig. 2 shows, is inconsistent with the assumption that the cosmic rays are absorbed like photons. In fact, the broken curve of Fig. 5, which represents a two component "Gold integral" curve, is approximately the best fit that is possible, assuming cosmic rays of the photon type, if we take the values at 5 cm, 45 cm and 70 cm pressure as experimentally fixed. The departures of this curve from the solid line representing the experimental data become as great as 30 percent, which is much larger than the experimental error.

It has been noted above that the wall of our ionization chamber was thick enough to reduce the transition effects almost to zero. It is worthy of note that Schindler's transition effect measurements extended to thicknesses of lead up to 36 cm, and showed no irregularity such as that appearing in our intensity data at 20–30 cm of mercury. There thus appears no reason to ascribe the downward curvature of our experimental log I *vs.* P curve in this region to a transition effect.

On the other hand, the experimental curve can be completely accounted for in terms of ionization by particles of the r-type. Gross notes[20] that the range distribution of the r-particles necessary to account for the ionization I is given by

$$R = -d\psi/dP, \tag{9}$$

where R is defined as in Eq. (6) and ψ as in Eq. (8). By using the dotted curve of Fig. 6 for ψ, which has been corrected for absorption in the chamber wall, Fig. 7 shows the corresponding range distribution as calculated by Eq. (9). That is, this curve (Fig. 7) represents the range distribution of the r-particles entering the atmosphere which would give the experimental ionization pressure curve.

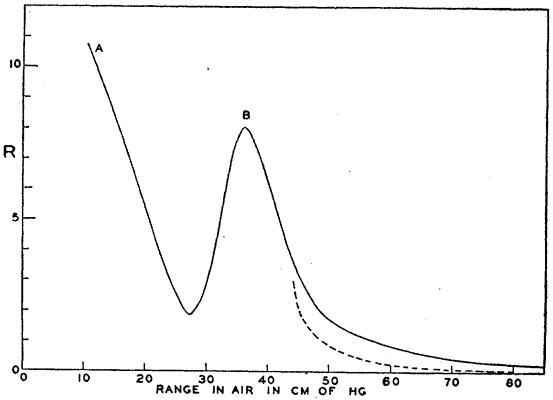

FIG. 7. Range distribution of ionizing particles entering atmosphere required to give observed ionization *vs.* altitude curve. Broken line, range distribution for component of cosmic rays deflected at equator by earth's magnetic field.

A straightforward analysis of our data in terms of r-particles thus shows, even after due allowance for the uncertainty of graphic differentiation, the presence of two sharply distinct range groups. One group A appears to have ranges of all values, with a maximum for very short ranges (less than 10 cm of mercury). In the other group B there appear to be no rays of range less than about 27 cm and a strong maximum at about 36 cm.

6. Origin of Range Group B

Clay's latitude effect, as confirmed and extended by our survey expeditions, has revealed a component of the cosmic rays which, being magnetically deflectable, must consist of electrically charged particles (more specifically, positively charged, in view of the Johnson-Alvarez-Rossi directional experiments). The theories of

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[20] B. Gross, reference 3, p. 217. We use expression (9) instead of (7) to calculate R because the derivation applies to a thin walled chamber. The R *vs.* r curve is deformed due to the effect of the wall if Eq. (7) is used.

Störmer,[21] Rossi,[22] Lemaitre and Vallarta[23] and others have shown that at a given latitude, particles with less than a certain speed are so deflected by the earth's magnetic field that they cannot reach its surface. Peak *B* of Fig. 7 can thus be explained as due to electrically charged particles which occur in space with a wide range of energies, of which however only those with kinetic energy equivalent to a range in air of more than about 27 cm of mercury are able to penetrate the magnetic barrier at a latitude of 52 degrees.

According to Lemaitre-Vallarta's Fig. 1, the intensity *vs.* latitude curve which is steepest at 52 degrees is that for which their function $x_0=2.1$. This value should correspond approximately to the peak of our range curve (Fig. 7). By their Table VI, the value of the function $x_0=2.1$ corresponds to the following energies:

Electrons or positrons,	2.6×10^9 e.v.
Protons,	1.9×10^9 e.v.
Alpha-particles,	2.6×10^9 e.v.

The energy that a particle must have for a range of 36 cm (peak *B*) can be estimated most directly from experiments such as those of Anderson, which measure the energy loss of cosmic-ray particles on traversing plates of lead. He finds[24] that for electrons with energies of the order of 3×10^8 volts the average rate of energy loss in lead is 3.5×10^7 electron-volts per cm. He has preferred to use however a calculated value of 2.0×10^7, and has told us in conversation that later experiments indicate that the value 3.5×10^7 is too high. We shall use the mean of these values, 2.8×10^7 electron-volts per cm of lead. Following Anderson's procedure, this corresponds to 5500 volts/cm in standard air, or 4.4×10^9 electron-volts to penetrate vertically through the atmosphere. To penetrate to 36 cm of mercury this means, for electrons, positrons or protons, an energy of about 2.1×10^9 electron volts. For alpha-particles the energy would need to be about 4 times greater, or 8.4×10^9 electron-volts.

Comparison of these values with those required by the magnetic deflection shows close agreement if the range group *B* is due to protons, an impossibly great difference in the case of α-particles, and a difference which is within the limits of error in the case of positrons or electrons. Noting that electrons are ruled out by the directional experiments, this means that the particles responsible for range group *B* are most probably protons. They cannot be alpha-particles. It is possible, but less probable, that they are positrons.

7. Ionization due to Cosmic-Ray "Protons"

The difference between the ionization measured at the geomagnetic latitude of our present experiments (52°N) and at the geomagnetic equator represents the ionization due to magnetically deflectable charged particles. If the above analysis is correct, these must be a part of those appearing in range group *B*. By comparing our present data with those which we obtained with similar apparatus on equatorial mountains we can determine the variation with altitude of the ionization due to this electrically charged component. In Fig. 8 are plotted *A*, the cosmic-ray ionization at geomagnetic latitude 52°N (from Fig. 5), *B* that at 3°S (from Fig. 6, reference 11, corrected for wall radiation of 0.14 standard ions), and curve *C* the difference

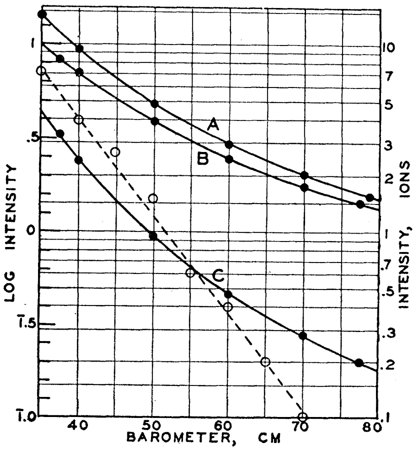

FIG. 8. Intensity *vs.* barometer curves for, *A*, high magnetic latitudes, *B*, magnetic equator, *C*, difference between *A* and *B*, showing that equatorial rays *B* are absorbed in same manner as magnetically deflectable rays *C*.

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

[22] B. Rossi, Acc. d. Lincei **15**, 62 (1932).

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

[24] C. D. Anderson, Phys. Rev. **44**, 409 (1933).

between the two ionizations. Curve C thus represents the ionization at different altitudes by rays which are known to be electrically charged, ionizing particles, and which are probably protons.

A similar comparison is possible from the airplane data recently published by Bowen, Millikan and Neher.[19] The dotted curve of Fig. 8 shows the difference between their values near the equator and at 42°N (geomagnetic). The differences between this and our curve C are partly ascribable to the different latitude range involved, and partly to the fact that our chamber was shielded by heavy lead walls. The curves however agree in showing an ionization altitude relation of an approximately exponential type. Since curve C is known to be due to charged particles, it is thus evident that we should err if we inferred from an exponential type of curve that it was due to photons.

Analysis of curve C according to expressions (8) and (9) gives the dotted line of Fig. 7. Since curve C is itself a difference curve, and since it is twice differentiated to obtain this dotted curve, slight experimental errors are greatly magnified. Nevertheless the trend of the curve is in good accord with the view that it is these magnetically deflectable particles which are responsible for the range group B.

Though the directional experiments of Johnson[25] and Rossi[26] have shown magnetically deviated particles at the equator, these must have ranges greater than the depth of the atmosphere. We should accordingly predict the absence of a hump due to the range group B appearing in high altitude measurements near the geomagnetic equator. The same reasoning indicates that the range corresponding to the maximum of this group should be shorter and the peak more prominent at high latitudes than at low latitudes.[27] High altitude experiments at different latitudes should thus give an important test of our interpretation of the origin of this peak.

8. Origin of Range Group A

From the shape of the curve of Fig. 7 it would appear possible that the radiation which is responsible for range group A may be almost completely absorbed in the upper part of the atmosphere. If this is true, we should need to account for the cosmic rays received at the equator as well as those at high latitudes in terms of the higher energy protons (or positrons) of group B, with the addition of the more penetrating radiations which do not show in this analysis. The strong directional effects observed near the equator by Johnson and Rossi lend support to this view.

That the nature of the cosmic rays at the equator is similar to that of the magnetically deflectable particles of group B is also shown by their similar absorption and transition effects. We have noted above the similarity in form of the absorption curves B and C of Fig. 8, which are due respectively to equatorial and to magnetically deviable cosmic rays. The similarity of their transition effects is shown by experiments made by our associated expeditions at various latitudes comparing the ionization with 1 and with 2 shields of 2.5 cm lead. The value of this ratio varies from 1.15 at sea level to 1.49 at 5800 meters, but shows no systematic variation with latitude. The measurements[28] given in Table I are typical. Since the fraction of magnetically deviable rays present in the cosmic rays is much greater at the higher latitudes, the constancy of this ratio i_1/i_2 means that the transition effect is substantially the same for the rays unaffected by the earth's magnetic field as it is for those which are thus affected.

TABLE I.

Place	Geomag. Lat.	Barometer	i_1/i_2
Mt. McKinley	67°N	50.0 cm	1.312
Jungfraujoch	49°N	50.0	1.302
Mt-aux-Sources	30°S	54.5	1.300
Chicla	1°S	48.6	1.312

The short range values of R (Fig. 7) are consistent with the assumption either that group A is electrically neutral (since no lower range

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[25] T. H. Johnson, Phys. Rev. **44**, 856 (1933).

[26] B. Rossi, Phys. Rev. **45**, 212 (1934).

[27] Examination of the data collected in Fig. 6 offers some support of this prediction.

[28] A. H. Compton, reference 11, Table III.

limit appears), or that it is due to particles of large ratio of mass to charge, such as α-particles or heavier nuclei. If these rays do not penetrate the atmosphere, we do not find any existing data on which to base a choice between these hypotheses. The graphic differentiation leading to Fig. 7 is however not sufficiently reliable to justify extrapolating range group A to zero. It is not impossible that they may constitute an important part of the rays at sea level which are not found to be appreciably affected by the earth's magnetic field. If this is the case, the similarity between the equatorial and the magnetically deviable cosmic rays would suggest that these neutral rays may consist of hydrogen atoms, which on entering the atmosphere are broken into their component protons and electrons. It would be difficult to reconcile this similarity with the assumption of any considerable photon or neutron radiation in the equatorial cosmic rays as observed at the earth's surface.

On this view the photons which occasionally show themselves in cloud expansion experiments would be secondary rays, of the nature of x-rays produced by the passage of the high speed protons and electrons through the matter above the expansion chamber. Some of Anderson's recent experiments[29] which indicate showers of photons from a common source give direct indication of such an origin. Rossi[26] has also felt the need of some such catastrophic act in the stopping of charged cosmic-ray particles. X-ray experiments, which show in the range of x-ray voltages an increase in efficiency of x-ray production proportional to the energy of the cathode rays, suggest that such a transformation of a cosmic-ray particle's energy into x-ray photons may be a highly probable event.

9. The Apparent Nature of the Cosmic Rays

Our ionization-altitude curve obtained on the Settle-Fordney stratosphere flight is thus found to be inconsistent with the view that the cosmic rays enter the atmosphere as photons. It is however explicable in terms of ionizing particles with a definite range. Direct analysis of the data shows the existence of a group of rays with ranges greater but not less than the air equivalent of about 27 cm of mercury. Comparison with the effect of the earth's magnetic field shows that these rays are probably protons, or possibly positrons. The remaining rays (group A) show no lower range limit, and are thus either electrically neutral, or have a large ratio of mass to charge. These rays seem to be more strongly absorbed than those of group B, and may be confined to the upper atmosphere. Our measurements would be consistent with the view that some of the cosmic rays which reach the earth's surface enter the atmosphere as hydrogen atoms. The similarity in properties of the equatorial cosmic rays with those which are magnetically deflectable, however, leaves no room for any considerable admixture of photons in the primary cosmic rays which reach the earth. These conclusions are in complete accord with the various coincidence experiments which have seemed to demand a corpuscular character for the cosmic rays.

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[29] C. D. Anderson and S. H. Neddermeyer, Phys. Rev. **45**, 295 (1934).

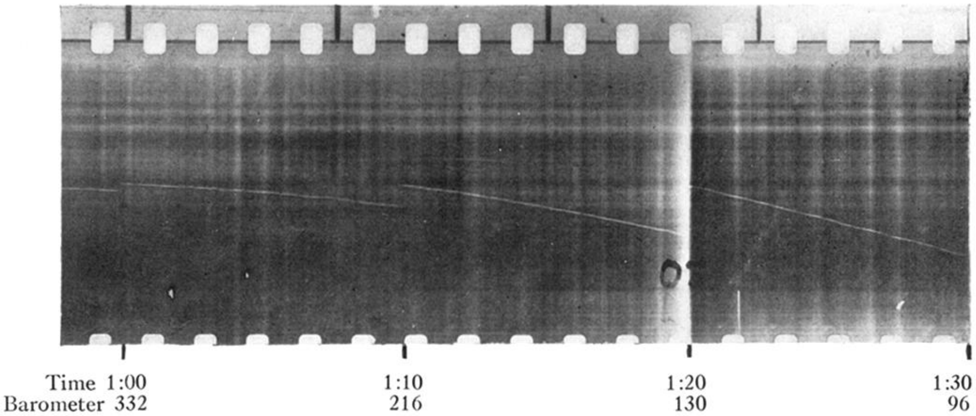

FIG. 4. Trace of shadow of electrometer needle during period of rapid ascension into stratosphere.