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# Coincidence Counter Studies of the Corpuscular Component of the Cosmic Radiation

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The directional distribution of the cosmic radiation has been investigated in Peru, geomagnetic latitude λ0°, atmospheric depths $h=6$, 6.8, and 10 meters of equivalent water; in Panama, λ20°, $h=10$ meters; in Mexico, λ29°, $h=6.8$, 7.2, and 10 meters; and in Pennsylvania and Colorado, λ50°, $h=10$, and 7.2 meters. At each location the west intensity exceeded the east and the percent asymmetry was maximum near zenith-angles of 45°, falling off towards the horizon. At $h=10$ meters the maximum asymmetry varied from 2 or 3 percent at λ50° to 8 or 10 percent at the equator and at $h=6$ meters it attained 16 percent at the equator. It is shown that the observations cannot be accounted for as an effect of secondary rays, and from the Lemaitre-Vallarta theory expressions have been derived which relate both asymmetry and latitude-intensity-variations to a primary corpuscular component. The discovery of the asymmetry therefore establishes beyond doubt the existence of this component, already indicated by the latitude effect. Consistency between magnitudes of the two effects can be established only if the corpuscular component is exclusively positive. The magnitude and the absorption coefficient of this component associate it with the intense soft component of the absorption curve analyses of Millikan and Regener, with coefficient 0.55 per meter of water and containing some 98 percent of the radiation incident at the top of the atmosphere. Although the corpuscular radiation is widely distributed in energy, close analysis shows a band of greater-than-average intensity in the range of positron or proton energies from 1 to $1.8\times10^{10}$ volts. Independent determinations of energy and absorption coefficient show disagreement in order of magnitude with the theory of energy loss by ionization, and the atmospheric range of the asymmetrical radiation is anomalously independent of primary energy. Both characteristics point to some other process for dissipation of energy. Studies have been made of the shower-producing radiation, and it is found that its absorption coefficient in the atmosphere agrees with that of the corpuscular component. The directions of shower-producing rays are likewise asymmetrically distributed showing them to be of positive corpuscular origin. Hence it is suggested that shower-production possibly accounts for the absorption anomalies. Studies of the shower-producing mechanism at high elevations have shown the existence of relatively soft intermediary rays which are also ionizing corpuscles. Studies of the zenith-angle distributions at high and low elevations have shown that the ratio of counts to electroscope ionization is less for the soft than for the harder components and a correction for this effect, probably arising from shower production, brings zenith-angle distributions into fair agreement with the absorption curve analysis of Bowen, Millikan and Neher. Difficulties in accounting for exclusively positive radiation by radioactive and secondary processes are enumerated and the existence of a radial cosmic electric field with the earth near its center is suggested. Acknowledgment is made of the support and cooperation of the Carnegie Institution, the Bartol Foundation, and of many individuals.

An asymmetry of the cosmic-ray intensity with respect to the meridian plane was to have been expected from Störmer's[1] theory of the orbits of electrically charged particles in the magnetic field of the earth if the primary radiation contained an electrically charged component with more rays of one sign than of the other. Primary electrons, protons, or alpha-particles in the energy range $5\times10^9$ to $5\times10^{10}$ volts would be asymmetrically distributed in the

[1] Carl Störmer, *Gerlands Beitrage zur Geophysik*, Ergebnisse der kosmischen Physik **I**, p. 1 (1931).

latitudes of the torrid and temperate zones, and if these rays or their secondaries could penetrate the atmosphere without appreciable changes of direction, the asymmetry would persist at sea level. Evidence for the existence of corpuscular rays of these energies had been found in the absorption experiments of Bothe and Kolhörster[2] and in the cloud photographs of Anderson[3] and Kunze,[4] and their presence in the primary radiation was the most natural interpretation of the latitude-intensity-variations found by Clay[5] and Compton,[6] particularly of the finding of the latter that the intensity depended upon geomagnetic rather than upon geographic latitude.

## 1. Earlier Measurements of the Asymmetry

Rossi[7] looked for an asymmetry of the radiation in Italy, but his experiments failed to show a difference between the east and west intensities. With an arrangement providing better resolution in zenith-angle, the writer and J. C. Street,[8] working on Mt. Washington, N. H., found slightly greater intensities from the west than from the east at zenith-angles of 30° and 40°, and in the light of the theory this indicated a greater intensity of positive than of negative primary rays in a narrow energy-range around $1.6\times10^9$ proton-volts.

## 2. Scope of Present Survey and Other Recent Work

Since the theory attributes both the asymmetry and the latitude-intensity-variation to the same component of the radiation, more pronounced asymmetries were to be expected in equatorial latitudes where intensity-variations are greater. Accordingly, a survey was undertaken during the spring and summer of 1933 to measure the asymmetry at various latitudes and elevations within the equatorial zone. The objectives were: (1) to obtain new evidence to supplement the latitude-intensity-variations in establishing beyond reasonable doubt the existence of a primary, corpuscular component of the radiation; (2) to determine the relative intensities of positive and negative components; (3) to determine the distribution in energy of radiation in the affected range ($5\times10^9$ to $5\times10^{10}$ volts, if electrons or protons); and (4) to determine the energy lost by corpuscular rays of these energies in their passage through the atmosphere.

Though still incomplete, the survey[9] now includes measurements at the magnetic equator in Peru at elevations corresponding to depths below the top of the atmosphere of $h=6$, 6.8 and 10 meters of equivalent water; in the Panama Canal Zone, geomagnetic latitude λ20°, $h=10$ meters; in Mexico, λ29°, $h=6.8$, 7.5 and 10 meters; and by Stevenson in Colorado and Pennsylvania, λ50°, $h=7.2$ and 10 meters. At each of the above locations an asymmetry has been found in the sense to agree with the Mt. Washington experiments, i.e., with the west intensity greater than the east. In Mexico measurements were made with independent apparatus by Alvarez.[10] An asymmetry at sea level at the equator has also been found by Auger and Leprince-Ringuet,[11] and Rossi[12] has reported measurements of the asymmetry in Erythrea, λ11° 30′, elevation 2370 meters. A. Ehmert[13] has also made measurements on the Zugspitse, λ48°, $h=7.3$ meters. All of the above results are in agreement with our own. Other measurements by Bennett and Stearns[14] in Colorado, and by Korff[15] in California and Arizona, though not in disagreement with those of Stevenson, were inconclusive in showing an asymmetry, because of larger probable errors.

[2] W. Bothe and W. Kolhörster, Zeits. f. Physik **56**, 776 (1929).

[3] C. D. Anderson, Phys. Rev. **41**, 405 (1932); **44**, 406 (1933).

[4] P. Kunze, Zeits. f. Physik **80**, 559 (1933).

[5] J. Clay, Proc. Roy. Acad. Amsterdam **35**, 1282 (1932).

[6] A. H. Compton, Phys. Rev. **43**, 387 (1933).

[7] B. Rossi, Nuovo Cimento **8** (3), 3 (1931).

[8] T. H. Johnson and J. C. Street, Phys. Rev. **43**, 381 (1933).

[9] Preliminary reports of the work have appeared as follows: T. H. Johnson, Phys. Rev. **43**, 834 (1933); J. Frank. Inst. **215**, 749 (1933); Phys. Rev. **44**, 856 (1933). E. C. Stevenson, Phys. Rev. **44**, 855 (1933). T. H. Johnson and E. C. Stevenson, Phys. Rev. **44**, 125 (1933).

[10] L. Alvarez and A. H. Compton, Phys. Rev. **43**, 835 (1933).

[11] P. Auger and L. Leprince-Ringuet, Comptes Rendus **197**, 1242 (1933); Nature **133**, 138 (1934).

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

[13] A. Ehmert, Phys. Zeits. **35**, 20 (1934).

[14] J. C. Stearns and R. D. Bennett, Phys. Rev. **43**, 1039 (1933).

[15] S. A. Korff, Phys. Rev. **44**, 515 (1933).

### 3. Apparatus and Experimental Procedure

The apparatus used in the survey consisted of a train of three Geiger-Mueller counters with a circuit[16] for selecting and recording the coincident discharges. In most of the measurements each element of the train consisted of a bundle of three small counters, individually provided with separate leak resistors and condensers coupling to a common amplifier. Because of low counting rates in consequence of the small size of each element, the efficiency of this arrangement, as limited by insensitive recovery time, was greater than that of single, large counters of the same cross-sectional area. Two different arrangements were used, represented by (a) and (b) Fig. 1. Arrangement (a), designed for good resolution in zenith-angle, consisted of three bundles of horizontal counters. The effective cross-sectional area of each bundle was 20 cm long by 5 cm wide and the outermost bundles were separated 25 cm. The angular aperture for which half or more of the area was effective was 11.5° in zenith-angle by 42°. In arrangement (b), for good resolution in azimuth, the axes of the counters were in a vertical plane and their line of centers was inclined 45°. In this case the effective area was 20 cm by 7.5 cm and the extreme bundles were separated 40 cm. This arrangement thus included rays in the range of zenith-angles 18°–72°.

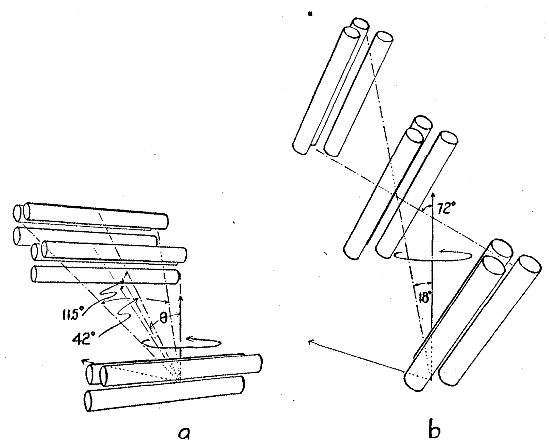


Fig. 1. Arrangements of counters: (a) for good resolution in zenith-angle; (b) for good resolution in azimuth.

[16] T. H. Johnson and J. C. Street, J. Frank. Inst. **215**, 239 (1933).

The counting rate of coincidences measured the intensity of radiation in the direction of the counter train, and intensities in different azimuths at the same zenith-angle were compared by frequent rotations about a vertical axis. This axis was adjusted to within a fifth of a degree of vertical by leveling screws, and the inclination of the counters was indicated by a protractor and spirit level. For greater speed in securing data three independent sets were operated simultaneously, and in the later measurements in Panama and Peru changes of orientation were made automatically at thirty-minute intervals and recording dials photographed at fifteen-minute intervals. The photographs also included the reading of a watch, the supply voltage, automatic azimuth indicators, and in some instances an aneroid barometer. 110 volt alternating current was supplied, when possible, by commercial lines and otherwise by a 500 watt, gasoline-electric generator. For most of the measurements in Peru and Mexico the apparatus was sheltered in a canvas tent. At the 6 meter elevation in Peru it was under a thin sheet-steel roof, and in Panama it was in a light, frame cottage. In none of the shelters could an asymmetry have been introduced by nonuniformly distributed, absorbing material.

### 4. Reduction of Data and General Conclusions

In reducing the data each pair of consecutive, fifteen-minute readings has been used for a value of the ratio of east to west intensity. These ratios are independent of the absolute sensitivity, and of long period changes of sensitivity, as well as of first-order, barometric changes, but statistical fluctuations produce spreads such as are indicated by the frequency-of-occurrence polygons of Fig. 2. In practically every case there is displacement of the center of the polygon to the left of unity, indicating a lower, average east intensity. The mean ratio of west to east intensity is tabulated in Table I, together with the number of data, $N$, and the probable error, $R$, of the mean as calculated from the observed spread of the data. The probable errors, $R'$, to be expected from statistical fluctuations alone (calculated from the total number of counts) are also given, and the agreement between $R$ and $R'$ is an

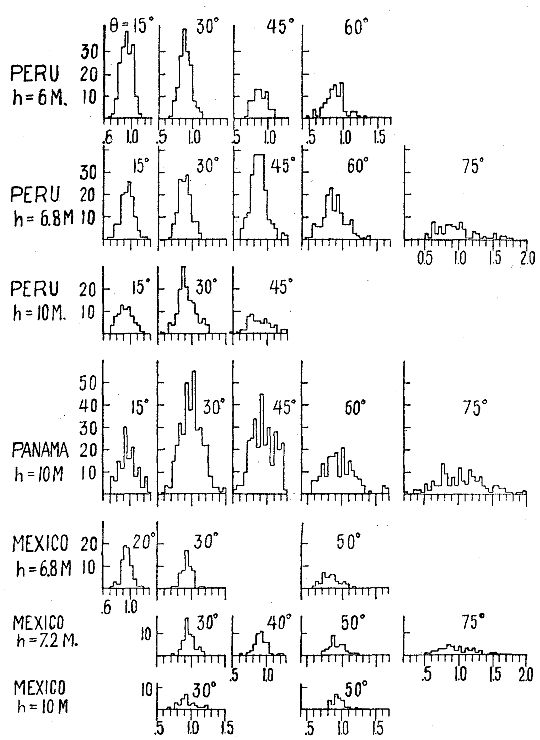

FIG. 2. Frequency-of-occurrence polygons showing distribution of ratios $j_e/j_w$.

important criterion of the absence of troublesome, short period, instrumental variations. In the case of some of the Mexican measurements, data for two or three adjoining zenith-angles have been clustered, as indicated by the footnotes of the table, to yield averages of higher precision. This is allowable since in none of these cases does the asymmetry vary by as much as the probable error over the range of zenith-angles included in a single average.

In Fig. 3, the ratio of west to east intensity for each location is plotted against zenith-angles, and the probable errors are indicated by the vertical lines. The data obtained in Mexico by Alvarez are represented by crosses, and the two data represented by circles, one in Peru at $h=6$ meters and the other in Mexico at $h=7.5$ meters, were obtained with 3.8 cm of lead inserted between the counters to absorb the softest component of the radiation. There is just an indication that this may be slightly diffused with respect to the primary directions since the asymmetries measured in this way are in both cases greater than without the lead. In most locations measurements at angles as great as 75° would have been partially obstructed by high horizons but the data at large zenith-angles are sufficiently complete to show definitely that the percent asymmetry diminishes towards the horizon. It is also definite, particularly from the Peruvian measurements, that the percent asymmetry increases with elevation, and both facts show the asymmetrical component to be softer than the average radiation. This is evidence that the asymmetrical component of the radiation is the same as that which varies in intensity with latitude, since the percent latitude effect is also greater at higher elevations.[6,17] It is also definitely established that the radiation is distributed more asymmetrically at the equator than at any of the other latitudes at which measurements have been made. At λ50° the maximum asymmetry is two or three percent, compared with fifteen percent at the equator.

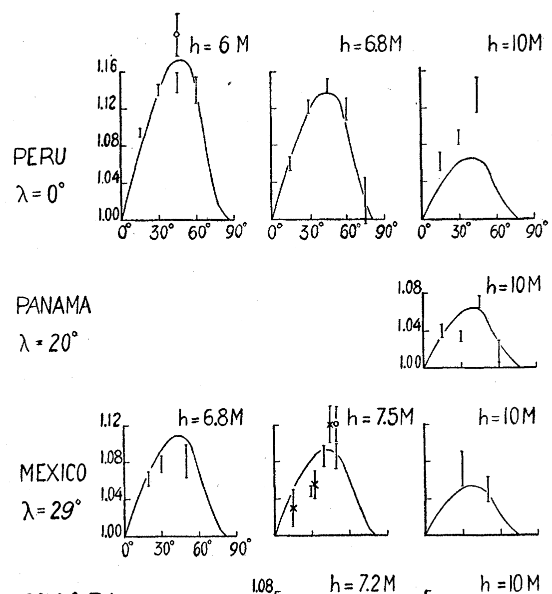

FIG. 3. Intensity ratios, $j_w/j_e$, *vs.* zenith-angle at various locations. Curves represent Eqs. (3), (5) and (6); lines, data without absorber; circles, data with 3.8 cm lead absorber; crosses, data of Alvarez.

[17] I. S. Bowen, R. A. Millikan and H. V. Neher, Phys. Rev. **44**, 264 (1933).

TABLE I. *Measured ratios of west to east intensity for various latitudes, elevations and zenith-angles.*

| λ | θ | $j_w/j_e$ | No. of data $N$ | Prob. error $R$ | Prob. error $R'$ | $j_w/j_e$ | No. of data $N$ | Prob. error $R$ | Prob. error $R'$ | $j_w/j_e$ | No. of data $N$ | Prob. error $R$ | Prob. error $R'$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $h=6$ meters | | | | $h=6.8$ meters | | | | $h=10$ meters | | | |
| 0° | 15° | 1.094 | 183 | .0054 | .0044 | 1.060 | 118 | .0069 | .0062 | 1.062 | 92 | .010 | .0096 |
| | 30° | 1.140 | 163 | .0064 | .0065 | 1.122 | 144 | .0073 | .0071 | 1.088 | 150 | .0085 | .0088 |
| | 45° | 1.148 | 72 | .0108 | .0102 | 1.145 | 218 | .0071 | .0072 | 1.134 | 63 | .019 | .0178 |
| | 45° | 1.200[a] | 45 | .023 | .0145 | | | | | | | | |
| | 60° | 1.140 | 93 | .014 | .013 | 1.119 | 150 | .0122 | .0121 | | | | |
| | 75° | | | | | 1.021[b] | 87 | .025 | .023 | | | | |
| 20° | 15° | | | | | | | | | 1.040 | 152 | .0076 | .0079 |
| | 30° | | | | | | | | | 1.034 | 328 | .0060 | .0058 |
| | 45° | | | | | | | | | 1.071 | 332 | .0068 | .0070 |
| | 60° | | | | | | | | | 1.018 | 191 | .0119 | .0125 |
| | 75° | | | | | | | | | .936[c] | 157 | .0185 | .0195 |
| | | $h=6.8$ meters | | | | $h=7.5$ meters | | | | $h=10$ meters | | | |
| 29° | 20° | 1.062 | 73 | .0077 | .0095 | | | | | | | | |
| | 30° | 1.078 | 54 | .0088 | .0099 | 1.048[d] | 59 | .0057 | .0084 | 1.072 | 30 | .019 | .019 |
| | 40° | | | | | 1.078[e] | 65 | .008 | .007 | | | | |
| | 50° | 1.081 | 41 | .018 | .015 | 1.086[f] | 38 | .014 | .013 | 1.050 | 25 | .014 | .017 |
| | 50° | | | | | 1.12[a] | 19 | .019 | .018 | | | | |
| | | | | | | $h=7.2$ meters | | | | $h=10$ meters | | | |
| 50° | 15° | | | | | | | | | 1.010 | 33 | .007 | .006 |
| | 30° | | | | | 1.022 | 26 | .006 | .006 | 1.031 | 35 | .0075 | .0075 |
| | 45° | | | | | 1.023 | 25 | .007 | .006 | 1.024 | 35 | .010 | .009 |
| | 60° | | | | | | | | | 1.010 | 27 | .015 | .014 |
| | 75° | | | | | | | | | 1.04 | 27 | .02 | .02 |

[a] 3.8 cm of lead inserted between counters.
[b] Horizon extended above horizontal 3° on the east and 5.1° on the west.
[c] Probably effected by a high horizon of dense tropical forest to the west.
[d] Includes 14 data at 25°.
[e] Includes 14 data at 35° and 36 data at 45°.
[f] Includes 19 data at 55°.

Besides comparisons of east and west intensities both arrangements, (a) and (b), Fig. 1, have been used for comparing intensities in other azimuths. These results are contained in Table IV.

## 5. PROOF THAT THE ASYMMETRY IS AN EFFECT OF THE PRIMARY RADIATION

From the Mt. Washington measurements we had concluded that although the observed asymmetry was characteristic of a positive, primary radiation, it could possibly have been accounted for as a secondary effect. For example, if the range of the secondary particle were at all comparable with its radius of curvature, an asymmetry in the observed sense would result if positive secondaries were either more abundantly produced or had larger ratios of range to radius of curvature than negatives.* This alternative can now be definitely discarded as an impossible explanation of the principal part of the observed asymmetries by the following reasoning. The action of the field on secondary rays would vary as the strength of the horizontal component of the field or approximately as cos λ. Hence, if we suppose the 2 percent effect at λ50° to be entirely due to secondaries, the maximum effect from secondaries at the equator would be 2 percent $\div$ cos 50° = 3 percent. This leaves the remaining 12 percent to be accounted for by primaries. On the other hand, with an asymmetry of 12 or 15 percent at the equator due to primaries, on the basis of assumptions concerning the penetration of the rays through the atmosphere which are in agreement with the latitude-intensity-variations, a 2 percent primary effect could be expected at λ50°. The secondary effect is, therefore, inadequate to account for the asymmetry at the equator and is not required to account for the asymmetry observed at high latitudes. Since approximately equal numbers of low energy positives and negatives have been found in cloud-

* A calculation of the asymmetry resulting from the deflection of secondaries produced in the atmosphere has been the subject of papers by B. Rossi and A. Garbasso, Rendi Lincei. **15**, 62 (1932) and by I. S. Bowen, Phys. Rev. **45**, 349 (1934).

chamber photographs by Anderson and Kunze, there is perhaps no reason to expect an asymmetry due to secondaries, but if some slight, secondary effect is also present it could possibly be distinguished by measurements at still higher latitudes, well above the parallel at which the intensity assumes its constant, high-latitude value.

## 6. Theory of the Asymmetry and Latitude Intensity Variations of the Primary Radiation

The theory of an asymmetry and a variation of intensity with latitude due to the influence of the earth's field on a primary, electrically charged radiation was given in approximate form by Störmer,[1] and by Epstein.[18] Important advances in the theory have been made by Lemaitre and Vallarta,[19] and although it is realized that further improvements in accuracy may still be forthcoming, for the purpose of the present calculations the results of the theory are represented by the curves of Fig. 4.[20] The parameter $x$, plotted as ordinate, is proportional to the square root of the radius of curvature of the particle in a magnetic field and, if the mass is large compared with the rest mass, $x$ is also proportional to the

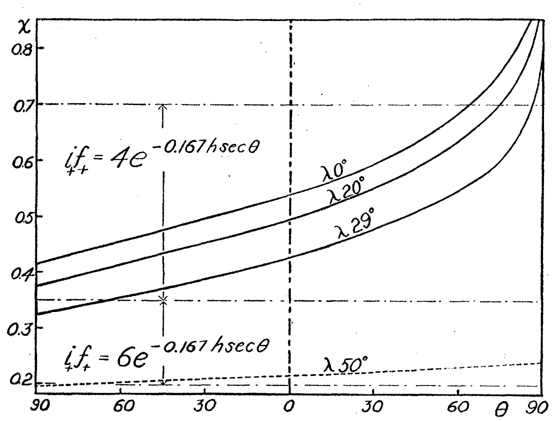


FIG. 4. Vallarta's curves, minimum values of $x$ vs. angle-from-meridian-plane and geomagnetic latitude. West is to the left for positive rays and to the right for negatives.

[18] P. S. Epstein, Proc. Nat. Acad. Sci. **16**, 658 (1930).

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

[20] M. S. Vallarta, Phys. Rev. **44**, 1 (1933). The dotted curve for $\lambda = 50°$ has been plotted from Störmer's equation.

square root of the energy. To this approximation the energy $E = 5.96 \times 10^{10}\, x^2$ volts. With the left side of Fig. 4 representing west, the curves give the minimum values, $x_0$, for which positive rays may reach the surface of the earth along the surfaces of cones at various angles $\theta$ from the meridian plane represented by the abscissae, and at latitudes represented by the various curves. The corresponding curves for negative rays are the images of these with respect to the line $\theta = 0$.

If we suppose the radiation to be more or less uniformly distributed in $x$, the curves of Fig. 4 provide the basis for expressions to represent both asymmetries and latitude-intensity-variations. Considering rays in the plane perpendicular to the meridian where zenith and meridian-angles are identical, if $i_+(x)dx$ and $i_-(x)dx$ represent the fractions of the total intensity from the zenith in atmosphere free space at latitude $\lambda$ on the surface of the earth due respectively to positive and negative primaries for which the parameter $x$ lies within the range $x$ to $x+dx$, and if the changes in these fractions due to filtering in the atmosphere over path lengths $h \sec\theta$ are given by factors $f_+(x, h \sec\theta)$ and $f_-(x, h\sec\theta)$, respectively, then the rate of increase of intensity, $j$ with $\theta$ at the zenith may be expressed as

$$(dj/jd\theta)_{\theta=0} = (i_+f_+ - i_-f_-)(dx_0/d\theta)_{\theta=0,\lambda=\text{const.}} \quad (1)$$

and the rate of increase of zenith intensity with latitude is expressed as

$$(dj/jd\lambda)_{\theta=0} = (i_+f_+ + i_-f_-)(dx_0/d\theta)_{\theta=0}. \quad (2)$$

Eq. (1) represents the slope of the asymmetry curves of Fig. 3, at $\theta = 0$, and (2) represents the slope of the latitude-intensity curve as determined by a train of counters pointing in the zenith direction.

The asymmetry at finite $\theta$ is given by the integral form

$$(j_{\theta w} - j_{\theta e})/j_{\theta e} = \int_{x_0(\theta_w)+}^{x_0(\theta_e)+} i'_+f'_+dx - \int_{x_0(\theta_e)-}^{x_0(\theta_w)-} i'_-f'_-dx, \quad (3)$$

where the limits of integration of the first term correspond to the ordinates of the positive curves of Fig. 4 for equal angles east and west, and those of the second term to the negative curves and $i'f'dx$ is the corpuscular component in range $dx$, expressed now as a fraction of the total radiation from the direction, $\theta_e$.

Similarly the intensity change at a particular angle for a finite change in latitude is represented by

$$(j_{\theta,\lambda_2}-j_{\theta,\lambda_1})/j_{\theta,\lambda_1} = \int_{x_0(\theta,\lambda_2)+}^{x_0(\theta,\lambda_1)+} i_+^* f_+^* dx + \int_{x_0(\theta,\lambda_2)-}^{x_0(\theta,\lambda_1)-} i_-^* f_-^* dx, \quad (4)$$

where $i^*f^*$ represents the intensity of the corpuscular component expressed as a fraction of the intensity at meridian-angle $\theta$ and at latitude $\lambda_1$.

Eq. (3) represents the asymmetry curves of Fig. 3, and Eq. (4) the latitude-intensity-changes as measured by a train of counters pointing in direction $\theta$. If (4) is averaged over all zenith-angles the result compares with intensity-variations measured with an electroscope.

Eqs. (1) to (4) contain the theoretical predictions for both latitude-intensity-variations and directional asymmetries, both effects being attributed to the same, corpuscular component of the primary radiation. The discovery of the latitude effect alone was a strong indication of the existence of this component since no other, completely satisfactory interpretation had been given, but *with the discovery of the asymmetry, the possibility of ever finding an alternative explanation for both effects, practically vanishes, and we may now regard the existence of a corpuscular component as substantially proven.* Furthermore, the asymmetry measurements show, by the greater western intensity, that the majority of the primary, corpuscular rays whose $x$ values lie within the range of variation of the curves of Fig. 4, carry a positive charge.

## 7. Evidence that the Corpuscular Component is Exclusively Positive

Eqs. (3) and (4) provide a means of comparison of the magnitudes of the asymmetry and the latitude-intensity-variations. The latter depend upon the sum of the positive and negative components, whereas the former depend upon their difference. A comparison of the two effects therefore leads to a determination of positive and negative intensities separately. Eqs. (1) and (2) provide an unambiguous method for making this determination but require measurements of the rate of change with latitude of intensity from the direction of the zenith and measurements of the asymmetry at small angles from the zenith. These quantities, at a particular latitude and elevation, then lead to values of the positive and negative intensities, $i_+f_+$ and $i_-f_-$, for the value of $x$ which becomes excluded from the zenith at that latitude.

On the basis of the data now available, it is more satisfactory to proceed with the analysis using the integral forms (3) and (4). Since the greater, western intensities appearing in the asymmetry measurements show that most of the corpuscular radiation is positive, it is convenient to try the assumption that it is exclusively so. This assumption reduces the right-hand members of (3) and (4) to the first terms and, if the assumption is correct, any empirical function, $i_+f_+$, which integrates over the limits of (3) to give observed values of the asymmetry, must also give observed latitude-intensity-variations if integrated over the limits of (4). If the assumption is not correct, but a negative component is also present, the function which integrates to give correct values of the asymmetry will give values for latitude-intensity-variations too small to agree with observation, and the percentage error will be twice the average ratio of the intensity of negatives to positives in the range of $x$ involved.

In seeking an empirical function it has been found that, if expressed as a fraction of the zenith intensity at the equator,

$$i_+f_+ = 4e^{-0.167h \sec\theta}; \quad i_-f_- = 0 \quad (5)$$

satisfactorily reproduce the observed asymmetries when used as the integrand of (3). The values calculated in this way are represented by the full curves of Fig. 3. Since Lemaitre and Vallarta's calculations have not extended to $\lambda 50°$ the dotted curves of Figs. 3 and 4 for this latitude are based upon Störmer's approximate equation. Here the integrand

$$i_+f_+ = 8e^{-0.167h \sec\theta}; \quad i_-f_- = 0, \quad (6)$$

has been used to give more satisfactory agreement with the observations. Although $x$ ranges from 0.2 to 0.7 between the extreme angles and latitudes of the observations, representing energies differing by a factor of ten, it is surprisingly unnecessary to invoke a variation of the exponential coefficient of (5) and (6) with $x$, and with the possible exception of the data for $h=10$ meters at the equator, the asymmetries calculated from (5) and (6) agree satisfactorily with the observations. Regardless of the significance of the constants in (5) and (6), the fact that this expression represents the correct magnitude of the asymmetrical component requires it to represent the component which varies with latitude, unless primary, negative radiation is also present. Between the equator and $\lambda 29°$ the value of $x_0$ for $\theta=0$ varies by $\Delta x_0=0.125$, and, from (4) and (5), the zenith intensity at sea level should increase at $\lambda 29°$ to 9.5 percent greater than its value at the equator. In agreement with this prediction, Auger and Leprince-Ringuet[11] have measured the latitude-intensity-changes with a train of counters pointing towards the zenith and have found an intensity at $\lambda 29°$ approximately 10 percent greater than that at the equator.

In order to compare with values observed by the electroscope method, (4) is averaged over all zenith-angles. Since the curves of Fig. 4, are nearly parallel, the average value of $\Delta x_0$ is about equal to its value at the zenith and the average fractional increase in intensity is

$$(J_\lambda - J_0)/J_0 = 4\overline{\Delta x_0} \int_0^{\pi/2} \sin z e^{-0.167h \sec z} dz \qquad (7)$$
$$= (2/\pi)\overline{\Delta x_0} G(0.167h).$$

Eq. (7) may be expected to apply to observations up to $\lambda 29°$. For higher latitudes the asymmetry data are less complete and theoretical curves perhaps less certain, but a greater intensity-factor is indicated in the range from $\lambda 29°$ to $\lambda 50°$. Since the factor, 8, in (6) represents the asymmetry data at $\lambda 50°$ and the factor, 4, in (5) is satisfactory at $\lambda 29°$ the value, 6, has been chosen to represent the corpuscular component for calculations of the latitude-intensity-variations in the range of $x$ between 0.2 and 0.35. The results of these calculations for two different elevations are contained in Table II, where they are compared with latitude-intensity-variations found by various observers. At each latitude and

Table II. *Comparison of observed latitude-intensity-variation (expressed as percent increases over the value at the equator) with values calculated from asymmetry, assuming an exclusively positive, corpuscular component.*

| Latitude | Depth meters of water | Calculated from (5) and (6) | Observed: Compton | Observed: Bowen, Millikan and Neher | Observed: Clay | Observed: Hoerlin |
|---|---|---|---|---|---|---|
| $\lambda 20°$ | 10 | 1 | 1 | 0 | 2 | 0 |
| | 6 | 3 | 3 | 0 | — | — |
| $\lambda 29°$ | 10 | 3 | 4 | — | 6 | 2 |
| | 6 | 7 | 10 | — | — | — |
| $\lambda 50°$ | 10 | 9 | 14 | 7 | 15 | 10 |
| | 6 | 23 | 33 | 25 | | |

elevation the agreement between the calculated and observed values is as good as that between the various observers. Therefore, in view of the assumption upon which the calculations are based, it is concluded that *within present accuracies of theory and experiment the positive component alone is sufficient to account for the entire variation of intensity with latitude*, and in the energy range extending from $x=0.2$ to 0.7 negative radiation, if present at all, cannot have more than a small fraction of the intensity of the positive radiation.

In estimating the accuracy of this conclusion, various considerations must be made. In the first place the calculations assume no change of direction by the primary and its secondaries during passage through the atmosphere. If such changes of direction are of significant magnitude their effect must diminish the asymmetry and any correction for diffuseness would lead to still higher estimates of the positive component. Previous measurements[21] of the angular distribution of the soft, secondary radiation have indicated that this is not appreciably diffused with respect to the average radiation but the two observations of the asymmetry with interposed lead indicate that a small correction of this nature may be required. As a second consideration the greatest discrepancy between observed and calculated asymmetry is for the ten meter depth in Peru, and this indicates a slightly greater, positive component at sea level than that represented by (5). In comparing counter and electroscope measurements in Table II, the ratio

[21] T. H. Johnson and E. C. Stevenson, Phys. Rev. **43**, 583 (1933).

of ionization-intensity to count-intensity has been assumed the same at all latitudes. The evidence presented in Section 15 indicates that soft radiation, present at high latitudes but not at the equator, produces a larger percent increase in ionization than in counts, and an allowance for this effect would again operate in the direction of increasing the estimated, positive component. On the side of the theory, inaccuracies in the curves of Fig. 4 would introduce errors into the calculated values of latitude-intensity-variations, but the writer is not in position to estimate the possible limits of errors of this nature. Without allowing for any of these considerations, the discrepancy between the calculated and Compton's observed value for λ29°, $h=6$ meters, requires a negative component equal to only 17 percent of the positive. The above considerations would place this estimate as the extreme upper limit of the negative component.

### 8. The Intensity of the Corpuscular Component

The range of $x$ within which observations of the corpuscular component are possible is limited on the lower side by atmospheric absorption at about 0.2 and on the upper side at about 0.75. Hence, it is not possible by direct observation of the asymmetry to determine the total intensity of the corpuscular component. However, if (5) and (6) are integrated over the range of $x$ within which they are observationally found to represent the corpuscular radiation, a lower limit is found for the intensity of this component at latitudes above λ50° where no part of it is excluded by the magnetic field. At sea level this calculation shows at least 37 percent of the vertical intensity and 13 percent of the intensity averaged from all directions to be corpuscular. At the elevation of 14,200 ft. ($h=6$) at least 58 percent of the vertical intensity and 33 percent of the average intensity is of the same character.

### 9. Absorption Coefficient of the Corpuscular Component

Since (5) and (6) represent the corpuscular component per unit range of $x$ expressed as a fraction of the zenith intensity at the equator, the exponential coefficient 0.167 per meter represents the difference between the absorption coefficient of the corpuscular component and the mean, effective coefficient for the average radiation. For the latter, the data of Bowen, Millikan and Neher for 6–7 meter depths with unshielded electroscope at the equator give by Gold integral analysis the value 0.35 per meter. The same value also reproduces the observed zenith-angle distribution with the best approximation realizable from a single component (see Table X, column V). The most probable coefficient of the corpuscular component is therefore about 0.52. Since values of the asymmetry are encumbered by rather high probable errors, some latitude is available in the choice of the coefficient in (5) and (6) but values greater than 0.25 and less than 0.10 can be definitely excluded. Also the value 0.167 has the support of the latitude-intensity-variations as measured at various elevations, since in Table II the agreements between observed variations and those calculated from (5) and (6) are as good at one elevation as at the other. Thus the absorption coefficient of the corpuscular component must be limited to values well within the limits 0.45 and 0.60 per meter.

### 10. Association of the Corpuscular Component with the Band Analysis of the Ionization Depth Curves

Recent studies of ionization *vs.* depth by Millikan and Regener and their associates[17, 22] have resulted in an analysis of the radiation into at least four distinct bands characterized by

Table III. *Data concerning the cosmic-ray bands.*
Analysis of Kramer given in ordinary and that of Bowen, Millikan and Neher, in italics.

| Component | I | II | III | IV | Corpuscular Component |
|---|---|---|---|---|---|
| Absorption coefficient per meter of water | 0.021<br>*0.0075* | 0.075<br>*0.03* | 0.157<br>*0.12* | 0.518<br>*0.55* | 0.52 |
| Intensity at $h=0$ (% of total) | 0.4<br>*0.02* | 3.3<br>*0.2* | 4.3<br>*1.1* | 92<br>*98.6* | |
| Intensity at $h=6$ (% of total) | 2.6<br>*1.5* | 17<br>*10.2* | 16.4<br>*23.3* | 64<br>*65* | greater than 33 |
| Intensity at $h=10$ (% of total) | 6.8<br>*5.2* | 39.5<br>*30.9* | 30.3<br>*44.5* | 23.4<br>*19.4* | greater than 13 |

[22] W. Kramer, Zeits. f. Physik **85**, 411 (1933).

values of intensity and absorption coefficient. In order, if possible, to identify the corpuscular radiation with one of these bands, data concerning them have been gathered in Table III and compared with the corresponding data of the corpuscular component.

It is clear from this comparison, as regards both absorption coefficient and intensity, that *if the corpuscular radiation is to be identified with a single band of the absorption curve analysis, this band must be the intense, soft component of coefficient 0.55* (0.518) *per meter of water which constitutes some 98 percent of the total radiation at the top of the atmosphere*, and which has heretofore[23, 24] been explained as a photon radiation of energy equivalent to the mass defect of helium with respect to four hydrogen atoms.

## 11. Energy Distribution of the Primary Corpuscular Radiation

Since the asymmetry measurements in the range of latitudes from the equator to λ29° are well represented by (5) if used as the integrand in (3), it follows that the corpuscular component must be approximately uniformly distributed throughout the corresponding range of $x$. These measurements, except at small zenith-angles, involve only the average intensity for rather wide ranges of $x$. Hence better resolution in $x$ was sought in a set of measurements, given in Table IV, which compare the intensities of closer azimuths. The same experimental procedure and method of reduction of data were used in this case as with the east-west measurements of Table I.

Corresponding to the azimuth $\phi$, measured from the east, the limit $x_0$ may again be determined from Fig. 4 by using the relation, $\sin\theta = \cos\phi \sin z$, in which $z$ is the zenith-angle and $\theta$ the angle of the ray from the meridian plane. The integration of (5) between these limits results in the "calculated" intensity-ratios and these epitomize the assumption of a uniform intensity-distribution in $x$.

Although the agreement of the calculated and observed ratios is fairly good, certain systematic discrepancies appear. For example, in the case of the Mexican data 1 and 5 the ratio W : S is less than predicted at both elevations whereas the ratios S : SE and S : E (data 2 and 3) are greater than predicted, and a similar effect is indicated by the data 9, 10 and 11. If the theoretical curves of Fig. 4 are correct, this would indicate the beginning of a band of greater-than-average intensity at about $x=0.43$ and extending to higher energies. At the equator systematic discrepancies again appear but in the reverse order. For each zenith-angle, measurements 23–28 indicate values of the ratio W : S greater than predicted and ratios S : E less than predicted, and a similar tendency is indicated by data 17–22 and 29–36. The data for the equator, therefore, indicate the termination of a band of greater-than-average intensity at $x=0.55$, extending from lower energies. *Thus there is definite indication of a band of greater-than-average intensity extending from* $x=0.43$ *to* 0.55 *corresponding to positron energies in the range 1 to* $1.8\times10^{10}$ *volts or to proton energies in the range 0.9 to* $1.7\times10^{10}$ *volts*. The data for Panama, in the center of this range of energies, are somewhat erratic and show no definite, systematic discrepancies of the same character as those exhibited by the other data.

At each latitude these measurements show the east to be the direction of minimum and west the direction of maximum intensities. Lemaitre and Vallarta have predicted a second order, southern effect in north latitudes, but data 6 and 7 have not confirmed this.

## 12. Consideration of the Loss of Energy by Corpuscular Rays

With independent determinations of primary energy and absorption coefficient, provided in the first instance by the Lemaitre-Vallarta theory and in the second by the measurements of asymmetry and intensity-*vs.*-latitude at various elevations, and with the knowledge that the rays are positive, it becomes of interest to see what conclusions may be derived regarding the processes by which energy is dissipated during passage through the atmosphere.

Considering ordinary scattering and ionization, Heisenberg[25] has given the theoretical relation for absorption coefficient as a function of energy $E$ for high speed electrons and the results may be expressed by $\mu=1/\text{range}=1/kE$, where $k$ has the

[23] R. A. Millikan and G. H. Cameron, Phys. Rev. **37**, 235 (1931).

[24] E. Regener, Phys. Zeits. **34**, 306 (1933).

[25] W. Heisenberg, Ann. d. Physik **13**, 430 (1932).

TABLE IV. *Distribution of intensity in azimuth compared with values calculated on assumption of uniform distribution in x.*

| Location | Datum number | Zenith-angle | Azimuths | Observed intensity ratio | Calculated intensity ratio | Probable Errors $R$ | $R'$ | No. of data |
|---|---|---|---|---|---|---|---|---|
| | | | | Arrangement (a) | | | | |
| Mexico | 1 | 45° | W : S | 1.024 | 1.04 | 0.0089 | 0.0094 | 38 |
| λ29° | 2 | " | S : SE | 1.10 | 1.04 | .012 | .012 | 30 |
| $h$=6.8 m | 3 | " | S : E | 1.08 | 1.06 | .018 | .014 | 11 |
| | 4 | " | SE : E | 1.020 | 1.023 | .0115 | .0113 | 29 |
| Mexico | 5 | " | W : S | 1.00 | 1.04 | .012 | .010 | 22 |
| $h$=7.5 | 6 | " | N : S | 1.00 | 1.00 | .011 | .010 | 22 |
| | 7 | " | SE : NE | .996 | 1.00 | .010 | .011 | 18 |
| | | | | Arrangement (b) | | | | |
| Mexico | 8 | | ESE : E | 1.00 | 1.00 | 0.021 | 0.018 | 33 |
| $h$=6.8 | 9 | | SE : ESE | 1.10 | 1.02 | .023 | .020 | 33 |
| | 10 | | SSE : SE | 1.035 | 1.025 | .020 | .019 | 33 |
| | 11 | | S : SSE | 1.023 | 1.018 | .021 | .019 | 33 |
| Panama | 12 | | W : SW | 1.045 | 1.010 | .0099 | .0102 | 200 |
| λ20° | 13 | | SW : S | 1.021 | 1.016 | .0149 | .0155 | 81 |
| $h$=10 | 14 | | S : SE | 1.041 | 1.022 | .0118 | .0118 | 145 |
| | 15 | | SE : E | 1.025 | 1.012 | .0110 | .0115 | 149 |
| | 16 | | NE : E | 1.062 | 1.012 | .025 | .026 | 33 |
| Peru | 17 | | S : SE | 1.022 | 1.045 | .013 | .012 | 136 |
| λ0° | 18 | | SE : E | 1.03 | 1.035 | .013 | .014 | 128 |
| $h$=6.8 | 19 | | SW : S | 1.005 | 1.034 | .013 | .012 | 97 |
| | 20 | | W : SW | 1.01 | 1.018 | .015 | .013 | 103 |
| | 21 | | SW : SE | 1.052 | 1.080 | .024 | .018 | 45 |
| | 22 | | W : E | 1.122 | 1.138 | .016 | .015 | 70 |
| | | | | Arrangement (a) | | | | |
| Peru | 23 | 30° | W : S | 1.050 | 1.046 | 0.0063 | 0.0076 | 110 |
| $h$=6.8 | 24 | 45° | W : S | 1.069 | 1.052 | .0076 | .0082 | 151 |
| | 25 | 60° | W : S | 1.055 | 1.035 | .018 | .021 | 49 |
| | 26 | 30° | S : E | 1.041 | 1.060 | .0099 | .0086 | 90 |
| | 27 | 45° | S : E | 1.061 | 1.082 | .0107 | .010 | 130 |
| | 28 | 60° | S : E | 1.048 | 1.062 | .023 | .024 | 37 |
| | | | | Arrangement (b) | | | | |
| Peru | 29 | | W : E | 1.15 | 1.165 | .015 | .014 | 71 |
| $h$=6 | 30 | | SW : SE | 1.095 | 1.10 | .013 | .015 | 50 |
| | 31 | | S : E | 1.06 | 1.08 | .016 | .014 | 56 |
| | 32 | | W : S | 1.052 | 1.063 | .019 | .019 | 26 |
| | 33 | | SW : S | 1.055 | 1.04 | .014 | .014 | 51 |
| | 34 | | S : SE | 1.092 | 1.055 | .018 | .018 | 35 |
| | 35 | | SE : E | 1.01 | 1.045 | .014 | .015 | 45 |
| | 36 | | W : SW | 1.02 | 1.02 | .009 | .009 | 112 |

slight logarithmic variation with energy given in Table V. For electrons of energies which enter into the asymmetry at the equator the calculated values of $\mu$ range from 0.02 to 0.05, values less than a tenth of 0.50 actually observed. For λ50° the calculated, absorption coefficients lie in the range 0.18 to 0.24, and, though closer to the observed value, still lie outside of the range of probable errors. Not only does the observed, absorption coefficient differ from that calculated for the equatorial energies in order of magnitude, but there appears to be no perceptible variation in this coefficient over a range of primary energies differing by a factor of ten. *If the primary radiation consists of positrons or protons these considerations therefore require that energy is lost through some other process than the ordinary ionization and scattering.*

TABLE V. *Absorption coefficients for high energy electrons, calculated on basis of ordinary ionization and scattering.*

| | | | | |
|---|---|---|---|---|
| $x_0$ | 0.217 | 0.306 | 0.434 | 0.61 |
| Electron energies $\times 10^{-9}$ volt | 2.8 | 5.6 | 11.2 | 22.4 |
| $k\times 10^{9}$ volt$^{-1}$ meters of water | 1.80 | 1.71 | 1.62 | 1.53 |
| absorption coefficient per meter of water ($\mu$) | 0.199 | 0.104 | 0.055 | 0.029 |

TABLE VI. *Intensity of showers at high and low elevations in Peru recorded by the apparatus of Fig. 5.*

| | Time (minutes) | Counts | Counts per min. | Probable errors $R$ | Probable errors $R'$ | No. of data |
|---|---|---|---|---|---|---|
| $h=10$ meters. Lead block $25\times10$ cm$^2\times1.3$ cm thick | | | | | | |
| Lead on | 1615 | 3971 | 2.46 | 0.031 | 0.026 | 77 |
| Lead off | 1212 | 675 | .56 | .014 | .014 | 77 |
| $h=6$ meters. Lead same as above | | | | | | |
| Lead on | 234 | 3623 | 15.50 | 0.22 | 0.17 | 16 |
| Lead off | 210 | 824 | 3.82 | .07 | .09 | 14 |
| $h=6$ meters. "Accidentals," one counter separated 8 ft. | | | | | | |
| | 102 | 56 | 0.55 | 0.04 | 0.05 | 7 |
| $h=6$ meters. Lead block $20\times5$ cm$^2\times3.8$ cm thick | | | | | | |
| Lead on | 690 | 4358 | 6.30 | 0.065 | 0.065 | 47 |
| Lead off | 713 | 2947 | 4.13 | .061 | .051 | 48 |

Moreover, the situation cannot be readily explained by supposing the radiation to consist of other types of positive particles. Although multiply charged atomic nuclei would lose energy in proportion to the square of the nuclear charge and it would be possible in this way to explain the high value of the observed, absorption coefficient, yet this theory could not account for the invariance of the absorption coefficient with latitude. If it were possible for heavy nucleus primaries to generate secondary electrons at the top of the atmosphere of about $10^9$ volts energy without themselves appearing in the measurements these would have about the coefficient observed. This theory is not tenable however since conservation of energy and momentum limits the maximum energy, $t$, imparted to a secondary electron of mass, $m$, by a nucleus of mass, $M$, and energy, $T$, to

$$t=(T+2Mc^2)/[1+mc^2(1+M/m)^2/2T] \quad (8)$$

and a secondary electron could receive an energy of only $10^8$ volts from a primary $10^{10}$ volt-proton while secondary energies from heavier primaries would be still more feeble. The most hopeful explanation of the absorption difficulties would seem to be some process whereby primary protons or positrons lose energy ten times more rapidly than would have been expected as a result of ionization and whereby the range is nearly independent of the initial energy.*

## 13. Shower Production by Corpuscular Rays

Since ordinary ionization is inadequate, it is of interest to investigate the production of showers as a possible explanation of these difficulties. To this end a study was made of the intensity of showers at two elevations to see if some correlation exists between the absorption coefficients of the corpuscular and of the shower producing radiations. For this purpose the arrangement of three, coincidence-bundles of counters in Fig. 5 was used and measurements were made in Peru at atmospheric depths $h=6$ and 10 meters. At the lesser depth, counts were recorded with and without lead of two different thicknesses placed above the counters as indicated, and at the lower elevation only the thinner lead was used. The results are recorded in Table VI. Comparing shower rates for the two elevations with the 1.3 cm thick lead block, 15.5 counts per minute were obtained at the six meter depth against 2.46 per minute at the ten meter depth. Because of a decrease in efficiency at the lesser depth, due to the increased, individual counting rate of each element, the shower rates must be multiplied by a factor, 1.1, to make them comparable with the sea-level rates. The data tabulated as "accidentals" were obtained with two of the counters in vertical contact and the third at a horizontal distance of 8 feet. It is quite probable that most of these counts are also due to showers, and no corrections to the shower rates have been applied on this account. These data are valuable, however, in showing that true accidentals do not contribute appreciably to the counts recorded as showers.

Corrected for efficiency, the shower rates at the two elevations are in the ratio 6.9 : 1, compared with the ratio 3.78 : 1 of coincidences for three, counter-bundles in line at these same elevations (see Table X). This means that the showers are produced by a radiation which is considerably softer than the average.

Since the apparatus discriminates in favor of

* *Footnote added in proof:* Simple calculation shows that a ray has a probability of 0.50 per water-equivalent-meter in air of passing within a distance of $2\times10^{-13}$ cm from the center of a nucleus. Since the radius of the nitrogen nucleus for disintegration by alpha-ray bombardment is of the order of $5\times10^{-13}$ cm, it seems reasonable to expect a corpuscular cosmic-ray, regardless of its energy, to have an absorption coefficient at least as great as 0.50 per meter due to nuclear collisions alone. For energies less than $0.6\times10^9$ volts the range as limited by ionization losses should correspond to absorption coefficients greater than this value and should be proportional to the energy. This would accord with the absence of magnetic effects at sea level at latitudes above $\lambda50°$.

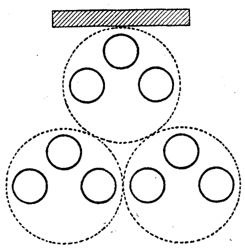

FIG. 5.

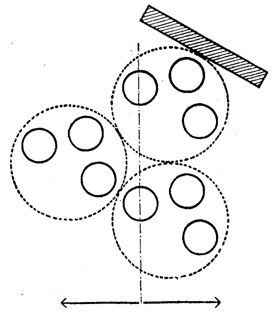

FIG. 6.

FIG. 5. Arrangement of coincidence counters for recording shower intensities.
FIG. 6. Arrangement of coincidence counters for observing asymmetry of shower-producing rays.

vertical rays, the absorption coefficient of the shower-producing radiation can be calculated with fair accuracy by the simple exponential law,

$$j_1/j_2 = e^{-\mu(h_1-h_2)}. \quad (9)$$

The above data with the 1.3 cm lead block thus result in an absorption coefficient of the shower-producing radiation of 0.49 and the data without lead in the value 0.50 per meter of water. With the same arrangement in Pennsylvania at sea level the coefficient for shower-producing rays has been determined from the barometer effect.[26] The results show a variation of shower intensity of 0.54 percent for a variation in barometric pressure of 1 mm Hg, and this corresponds to an absorption coefficient of 0.41 per meter of water.

The agreement of these values with the coefficient calculated from the asymmetry in Section 9, is striking evidence that the *corpuscular component is the principal source of showers*, and would suggest that shower-production may be the explanation of the anomalous rapidity with which these rays are absorbed.

Further evidence for identifying the shower-producing radiation with the corpuscular component has been found in an asymmetry with respect to the meridian plane of the directions of the shower-producing rays at the equator and sea level. For this study the coincident bundles were arranged as indicated in Fig. 6. The block of lead was inclined 30° from the vertical exposing a greater surface to rays incident from one side than from the other, and the arrangement was rotated about a vertical axis back and forth between the east and west azimuths at the usual intervals. The results are recorded in Table VII.

[26] To appear soon.

TABLE VII. *Data showing the asymmetry of shower-producing rays at sea level on the equator.* Area of each counter bundle 20×7.5 cm² lead block 25×10×1.3 cm³.

| Azimuth | Time min. | Counts | Counts per min. | Probable errors $R$ | Probable errors $R'$ | Counts per min. due to lead |
|---|---|---|---|---|---|---|
| East | 2144 | 3392 | 1.58 | 0.018 | 0.018 | 1.03 |
| West | 2198 | 3661 | 1.66 | .018 | .018 | 1.11 |
| Without lead (Table VI) | | | 0.55 | | | |
| Ratio W : E | 1.08±0.025 | | | | | |

The 0.55 showers per minute, produced in the material of the counters and surroundings and recorded with no lead, have been subtracted equally from both east and west rates to give the shower rates due to lead alone. The west rate is thus 8 percent greater than the east rate, showing an asymmetry of the same order as that observed at this location for the total radiation. But this value must be regarded as a lower limit, since the true asymmetry may be masked to a considerable extent by diffuseness of the shower particles. *These data, therefore, lend additional support to the conclusion that the showers are produced principally by the corpuscular component.*

## 14. Studies of the Shower-Producing Process

As other investigators[27] have previously pointed out, showers are not produced directly by corpuscular rays of which the absorption coefficient is the order of 0.50 per meter of water, but the process is complex and involves the intermediary of a much softer radiation. In the present measurements the same conclusion is reached by comparing shower rates due to lead of two thicknesses. Table VIII gives shower rates for the 6 meter depth at the equator based upon the data recorded in Table VI, but reduced to unit lead area in the one case and to unit lead volume in the other.

[27] B. Rossi, Zeits. f. Physik **82**, 151 (1933). H. J. Bhabha, Zeits. f. Physik **86**, 120 (1933). J. H. Sawyer, Jr., Phys. Rev. **44**, 241 (1933).

TABLE VIII.

| Dimensions of lead | Shower rate due to lead | Rate per unit area | Rate per unit vol. |
|---|---|---|---|
| 5 cm×20 cm ×3.8 cm thick | 2.17 per min. | .022 | .0057 |
| 10 cm×25 cm ×1.3 cm thick | 11.68 per min. | .047 | .039 |

Under both reductions the thin block has the greater effect and this is interpreted that the intermediary rays which produce the showers have a higher equilibrium intensity in air than in lead and their reduction by the thick lead is several times that by the thin.

It has been suggested[28] that shower producing intermediaries are non-ionizing rays of the nature

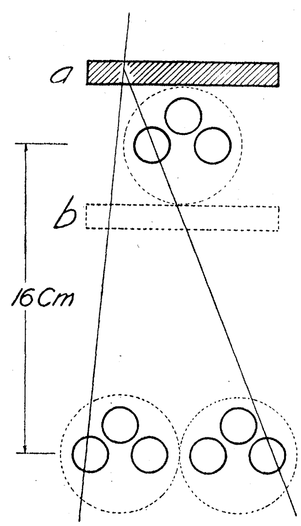


FIG. 7. Arrangement of coincidence counters for investigating ionizing character of shower-producing, intermediary rays.

of photons or neutrons. To make a test of this suggestion an experiment was made at the 6 meter depth on the equator, using the arrangement represented in Fig. 7. Triple coincidences were recorded (1) with the lead block in position (a), (2) with the lead block in position (b), and (3) without lead. Assuming the shower particles to continue principally downwards, the counts recorded with the lead in position (b) must be due for the most part to ionizing primaries which have themselves passed through the upper counter and subsequently have generated a divergent shower in the lead. Counts recorded with the lead in the upper position, on the other hand, include showers produced by both ionizing and non-ionizing rays without discrimination. A summary of the results is contained in Table IX.

TABLE IX.

| | Time (minutes) | Counts | Rate | Corrected rate |
|---|---|---|---|---|
| (1) Lead above position (a) | 145.4 | 780 | 5.36±.17 | 5.36 |
| (2) Lead below position (b) | 186.7 | 567 | 3.04±.086 | 4.13 |
| (3) No lead | 76.8 | 84 | 1.09±.11 | |

Dimensions of lead 25 cm×10 cm×1.3 cm
Dimensions of counters 20 cm×5 cm, separated 16 cm vertically

Without lead most of the showers recorded presumably originate in the material of the upper counter. From these, the lead in position (b) tends to shield the lower counters. On the other hand the 1.3 cm of lead in position (a) would have small effect in stopping intermediary shower-producing rays from generating the same number of rays in the material of the upper counter as are recorded without lead. The "no lead" data have therefore been used as an additive correction only to the counts recorded for position (b). The corrected shower rates recorded in the last column of Table IX indicate practically as many showers in the lower as in the upper position of the lead, and this is interpreted that *most of the intermediary rays are ionizing.** The slight excess recorded in the upper position could be accounted for by portions of the lead in this position protruding beyond the sides of the counter and being effective for the production of recorded showers because of the divergence of the shower particles. This process is illustrated by ray paths represented in Fig. 7.

[28] G. L. Locher, J. Frank. Inst. **216**, 673 (1933). Blackett and Occhialini, Proc. Roy. Soc. **A139**, 699 (1933). Bhabha, reference 27.

* It must be emphasized that this conclusion depends upon the above assumption that the showers proceed principally downwards, and, should this be found not to be the case, the experiment would lose in significance.

TABLE X. *Zenith-angle distributions at two elevations on the equator.*

| Zenith-angle | Time min. | Counts | I Counts per min. | No. of data | Probable Error $R$ | $R'$ | II Corrected rate | $F(z)$ | III $j(z)$ $\times 10^3$ | IV Analysis of B. M. & N. corrected for showers | V One component analysis $j=299\,e^{-0.35\,h\,\sec z}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Sea level, $h=10$ meters | | | | | | |
| 0° | 1328 | 9618 | 7.25 | 42 | 0.052 | 0.050 | 7.25 | 0.00133 | 9.65 | 9.65 | |
| 15° | 291 | 1991 | 6.85 | 16 | 0.10 | 0.10 | 6.85 | .00132 | 9.01 | 8.92 | |
| 30° | 1432 | 7603 | 5.30 | 48 | 0.049 | 0.041 | 5.30 | .00130 | 6.90 | 7.08 | |
| 45° | 1224 | 4277 | 3.49 | 69 | 0.032 | 0.036 | 3.49 | .00128 | 4.47 | 4.97 | |
| 60° | 360 | 676 | 1.88 | 24 | 0.037 | 0.046 | 1.88 | .00125 | 2.36 | 2.98 | |
| 75° | 433 | 254 | 0.59 | 10 | 0.022 | 0.025 | 0.59 | .00123 | .73 | .99 | |
| | | | | | 14,200 ft. $h=6$ meters | | | | | | |
| 0° | 1262 | 30477 | 24.10 | 98 | 0.091 | 0.093 | 27.40 | same as | 36.4 | 36.4 | 36.4 |
| 15° | 476 | 10448 | 21.90 | 34 | 0.15 | 0.15 | 24.80 | above | 32.8 | 33.7 | 33.8 |
| 30° | 526 | 8580 | 16.30 | 38 | 0.124 | 0.120 | 18.45 | | 24.1 | 24.9 | 26.8 |
| 45° | 520 | 5181 | 9.97 | 36 | 0.079 | 0.093 | 11.28 | | 14.4 | 14.4 | 15.4 |
| 55° | 245 | 1570 | 6.40 | 18 | 0.076 | 0.125 | 7.25 | | 9.13 | 8.70 | 7.68 |
| 60° | 801 | 3973 | 4.95 | 57 | 0.057 | 0.053 | 5.60 | | 7.00 | 6.55 | 4.47 |
| 75° | 493 | 960 | 1.95 | 35 | 0.041 | 0.042 | 2.20 | | 2.72 | 2.42 | .09 |
| 90° | 249 | 160 | .64 | 17 | 0.051 | 0.033 | .72 | | .90 | 0 | 0 |

## 15. Comparison of the Total Count-Intensities and Distribution with Respect to Zenith-Angle at 6 and 10 Meter Depths

A study of the distributions of the cosmic radiation in zenith-angle at different elevations was begun in 1932 by the writer[29] on Mt. Washington, using the coincidence-counter method. Previously Steinke[30] had made a similar study with a partially shielded electroscope. In continuation of the former work, the measurements recorded in Table X were made in Peru at elevations of 14,200 ft. and sea level corresponding approximately to depths of 6 and 10 meters. For these measurements, the counter train was oriented in the north azimuth.

Since the data for each location were obtained in a continuous run, the relative values for different zenith-angles are, without question, correctly measured. In making comparisons between the intensities for the two locations it is necessary to consider the possibility of changes of sensitivity. Thoroughly reliable results would require the transportation of the instrument back and forth from one location to the other several times, to insure against possible changes of sensitivity. Since it was inconvenient to do this, a check was obtained by making the measurements at each location with two instruments. Since no important change in relative sensitivity of the two instruments occured during transportation it is assumed that both remained constant, except for the change due to different counting rates of each element at the two elevations. This change in sensitivity is associated with recovery time and can be accurately determined by artificially raising the counting rates of each element, using radium, at the lower elevation to the high elevation rates and noting the effect of this on the number of cosmic-ray coincidence-counts. In this way it was found necessary to multiply the high elevation counts by the factor 1.13 to make them directly comparable with the low elevation counts. The counts per minute corrected for this effect are recorded in column II.

If the angular aperture of the counter train were infinitesimal, counting rates would convert into intensities, $j(z)$, through division by area and solid angle of the train. With the arrangement used, a correction for finite length of counters is required as previously described.[29] The conversion factors are functions of zenith-angle and are recorded as $F(z)$ in the table. These convert counts per minute into intensities, $j$, defined as the number of rays per $cm^2$ per unit solid angle per sec. (column III).

The distributions at the two elevations are shown graphically in Fig. 8 where sea-level rates have been increased by the factor 3.78 to

[29] T. H. Johnson, Phys. Rev. **43**, 307 (1933).

[30] E. G. Steinke, Zeits. f. Physik **48**, 647 (1928).

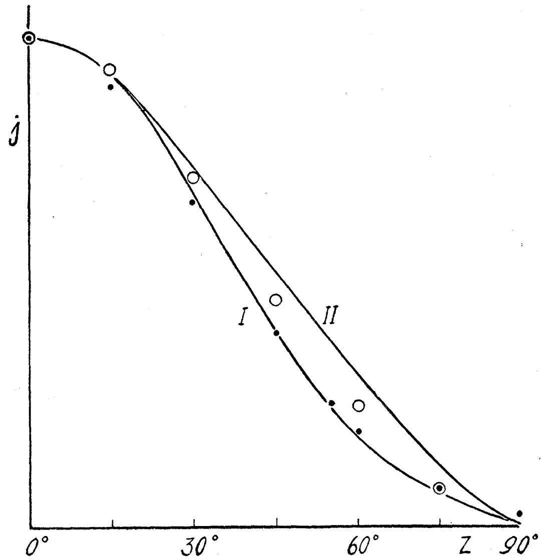


FIG. 8. Intensity *vs.* zenith-angle for two elevations at the equator. Dots, observations for depth $h=6$ meters; circles, seal-level observations $\times 3.78$; curve I, modified analysis of Bowen, Millikan and Neher for $h=6$ meters; curve II, same analysis $\times 3.78$ for $h=10$ meters.

bring vertical rates for the two elevations to the same value. A greater concentration about the vertical is observed at the higher elevation, and since any homogeneous radiation would become more broadly distributed in zenith-angle at the higher elevation, the observed, reverse effect is an indication of the composite nature of the radiation and of the existence of an intense, soft component, already revealed by electroscope measurements.

The distribution of a single component of coefficient $\mu$ is represented by

$$j(z)=j_0 e^{-\mu h \sec z}$$

and the distribution of a composite radiation, by the sum of a number of such terms corresponding to the several components. The four components given for the radiation at the equator by Bowen, Millikan and Neher and expressed in terms of ions per cc in normal atmospheric air due to radiation included in unit solid angle, are (I) $0.0318\ e^{-0.0075\ h \sec z}$, (II) $0.303\ e^{-0.03\ h \sec z}$ (III) $1.83\ e^{-0.12\ h \sec z}$, and (IV) $159\ e^{-0.55\ h \sec z}$ where $h$ is expressible in meters of water. Assuming the ratio of count-intensity to ion-intensity to be the same for each component, the intensities at different zenith-angles have been calculated by summation of the above terms. If the calculated intensities are adjusted to agree at the zenith with that observed at sea level, they are too high by a factor 1.20 to agree with the intensities observed at $h=6$ meters. In other words, *rays counted at a depth of 6 meters produce, on the average, 1.2 times as many ions as rays counted at a depth of 10 meters.* This effect also appeared as a result of the Mt. Washington studies. The phenomenon may be simply understood, as suggested in the earlier paper, in the following way. The component (IV) of the above analysis represents 65 percent of the total ionization at the six meter depth and in all probability, as shown in Section 10, consists of positive, corpuscular, shower-producing radiation. Since a shower is recorded in an electroscope in proportion to the number of ionizing rays associated with it, whereas it can never produce more than a single count on the coincidence-train it follows that this component must have a different ratio of counts to ions than that which holds for the other harder components which are not shower-producing. For comparison with counter measurements, therefore, the intensity of this one component requires modification. If it is arbitrarily supposed that for each ray of this component which is counted, 1.82 rays on the average would have passed through the ionization chamber, then the ion-intensity factor 159 should be divided by 1.82 to give a count-intensity factor bearing the same ratio to ion-intensity as that which holds for the other components. With this modification, the intensity of component IV is given by the factor 87.2 and the resultant intensities, in this instance adjusted by the same factor to agree with zenith intensities at both elevations, are given in Table X column IV, and plotted as curves I and II, Fig. 8. Although the agreement with the observed values is improved by this modification, there are still systematic discrepancies between observed and calculated intensities at sea level indicating the necessity of further slight modifications in the constants of some of the above components.

## 16. Conclusion

In conclusion, these studies show that the primary corpuscular component of the cosmic radiation in the energy range 0.5 to $5\times 10^{10}$ volts is very largely and probably exclusively positive. The intensity and the absorption coefficient of the positives identify them with the intense soft component which has been found to contain over 90 percent of the total radiation incident at the top of the atmosphere, and there remain at most but a few percent to be accounted for in some other way, possibly as a photon component. The basis for speculation as to the origin of the cosmic radiation and its energy content thus takes on a new aspect. In the first place it would be difficult to reconcile these findings with the hypothesis that the corpuscular rays are generated in interstellar matter by primary photons, since this process would produce negatives as well. Also radioactive processes, annihilations and transformations of nuclei, would have been expected to yield positives and negatives in nearly equal numbers. A remaining possibility is that of an electric field to accelerate positive, interstellar, gas ions in the direction of the earth. A radial field about the earth as center would produce rays with original directions limited to the zenith, and deflections in the magnetic field would produce a spread of directions between the meridian plane and the west horizon, with no possibility of rays entering from the east. The observed distribution could be accounted for if the field were due to a negative space charge pervading and surrounding the galaxy. Suggestions for the maintenance of charge on stellar bodies have been made by Swann[31] and Franck[32] and Swann has discussed the distribution of space charge resulting from the emission of negatives from positively charged bodies. On the other hand, Gunn[33] has raised objections against the existence of interstellar fields.

If cosmic-ray energies are acquired by acceleration in stellar or galactic fields, estimates of the total energy content, based upon the assumption of uniform distribution of the radiation throughout space, will require revision.

## 17. Acknowledgments

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[31] W. F. G. Swann, Phys. Rev. **45**, 295 (1934).

[32] J. Franck, Discussion at Boston Meeting of Am. Phys. Soc. held December 28–30, 1933.

[33] R. Gunn, Terr. Mag. and Atm. Elect. **38**, 347 (1933).