shows that the variation of the rates with absorber thickness is independent within statistics of the requirement that the events be associated with an air shower. This result is in agreement with the conclusion reached in I that these events associated with the discharge of counters in the extension tray are due to the $N$ rays in air showers.[15–17] While the electrons discharge the extension tray, the $N$ rays through their nuclear interactions give rise to the $AIB$ coincidences as in the case of unassociated events.

Two or more counters in the shielded tray $C$ were struck in 65 percent of the $AI_{0.3}B$ events associated with air showers, but were struck in only 30 percent of the $AI_{0.3}B$ events not associated with air showers. This result is in agreement with other observations showing that large penetrating showers are more frequently associated with air showers than are small penetrating showers.[17]

The rate of events associated with air showers in which only one tube in tray $A$ is struck ($A_1I_{0.3}BE$ events) is negligible, as would be expected.

Since the events associated with air showers are believed to be due to the $N$ component, they have not been subtracted from the coincidence rates. An analysis of the data in terms of unassociated events would not alter any of the conclusions we have obtained above.

[15] Cocconi, Tongiorgi, and Greisen, Phys. Rev. **75**, 1063 (1949).
[16] G. Cocconi and V. C. Tongiorgi, Phys. Rev. **79**, 730 (1950).
[17] Greisen, Walker, and Walker, Phys. Rev. **80**, 535 (1950).

### (6) The Pulse-Height Distribution

Data were also obtained for the events listed in Table I for different minimum voltage pulses from the ionization chamber. In addition to the coincidences with the $I_{0.3}$ pulses, results were obtained for coincidences with $I_{0.6}$, $I_{0.9}$, $I_{1.2}$ pulses (see Table I for definition of these terms). In agreement with I these results indicate that within the experimental errors the shape of the pulse-height distributions for a given coincidence event is independent of the absorber thickness. Thus the pulse-height distributions given in I apply here.

The pulse-height distributions for events associated with air showers are much flatter than those for events not associated with air showers. Thus, while only ($6.7\pm0.6$) percent of the $AI_{0.3}B$ coincidences are associated with air showers, ($14\pm2$) percent of the $AI_{1.2}B$ coincidences are associated with air showers.[18]

The experiment discussed in this paper was performed at the Inter-University High Altitude Laboratory at Echo Lake, Colorado. The author wishes to thank Professor Bruno Rossi for his continual and generous help and encouragement. Much of the apparatus was designed by Dr. H. S. Bridge, whose continued interest in this work is greatly appreciated. The author was fortunate in having the assistance of Mr. Daniel T. Anderson in performing the experiment.

[18] These results are for 0 g cm$^{-2}$ oil absorber.

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# Cosmic Radiation at Very High Altitudes Near the Geomagnetic Equator*

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During an extensive series of balloon-flights near the geomagnetic equator in India, intensity-depth curves have been obtained with the standard quadruple coincidence counter trains, containing various thicknesses of interposed absorber (4.0 cm, 7.5 cm, and 17.7 cm of Pb), previously utilized at high latitudes. A rather pronounced difference occurs between the two stations at Aligarh, Uttar Pradesh ($\lambda=18°$ N) and Bangalore, Mysore ($\lambda=3°$ N). The primary flux values, extrapolated to the "top of the atmosphere" from data obtained with instruments containing 7.5 cm of Pb, are $0.032\pm0.001$ and $0.024\pm0.001$ cm$^{-2}$ sec$^{-1}$ sterad$^{-1}$, respectively.

A maximum appears in all of the curves, and the general features, as well as the absorption characteristics of the cosmic rays in the upper atmosphere, are in accord with expectation. The effective absorption length in lead, approximately 290 g cm$^{-2}$, remains unchanged when the geomagnetic cut-off energy of the primary protons is increased from 1.4 Bev to 14.2 Bev. The intensity of mesons having energies exceeding 260 Mev is determined from the data by invoking Messel's theory of the nucleon cascade, and this yields results which are in excellent agreement with the available experimental facts.

The primary magnetic-rigidity spectrum averaged over the range 2.1 Bv to 15.4 Bv is $N(>pc/Ze)=0.68(1+pc/Ze)^{-1.2}$, based upon the present measurements at 52° N and 3° N. However, the data recorded within the equatorial region require a higher value of the corresponding exponent in the differential distribution if the usual assumptions are valid. This effect may be attributable to an irregularity in the primary spectrum, contributions from trapped orbits and albedo, or local magnetic anomalies.

The ratio of intensities in the horizontal and vertical directions at high altitudes is practically equal at 52° N and 3° N, although it would have been expected to increase near the equator in view of the decrease previously observed north of 52°.

## I. INTRODUCTION

INVESTIGATIONS of the variation with latitude of the intensity and properties of various components of the cosmic radiation have yielded a considerable amount of information regarding the primary particles. In particular, the only direct method available for the

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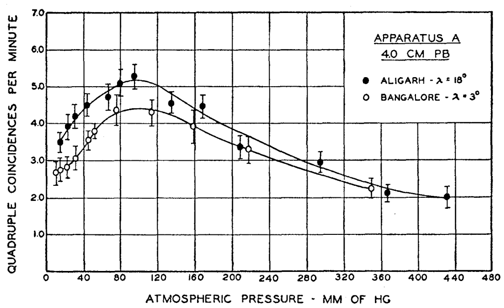


FIG. 1. Vertical counting rate as a function of atmospheric pressure, at two stations in India, for cosmic rays penetrating 4.0 cm of Pb. The experimental points represent the combined data obtained in separate balloon flights.

determination of the distribution in energy of the bulk of incoming protons utilizes observations of the vertical intensity at the highest accessible altitudes at different latitudes. On the basis of geomagnetic theory, which defines the corresponding minimum momenta required for arrival, the energy spectrum can be determined,

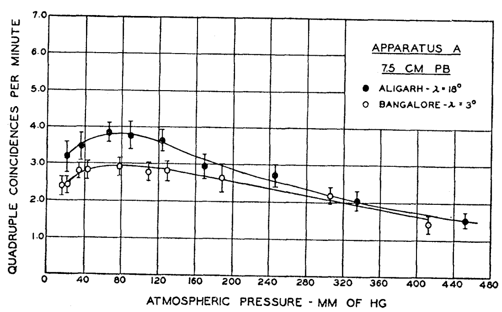


FIG. 2. Vertical counting rate *vs* atmospheric pressure, for particles having residual ranges exceeding 7.5 cm of Pb. The maximum observed at 3° and 18° does not appear at high latitudes.

subject, however, to certain qualifications imposed by the assumptions which must be invoked.

Thus, the measurements obtained by Winckler *et al.*[1] with balloon-borne instruments at atmospheric depths of 15 g/cm$^2$, and by Van Allen and Singer[2] with rockets indicated that the primary spectrum could be represented by a power law in which the total flux of particles having energy exceeding $E$ is approximately inversely proportional to $E$, where 14 Bev$>E>$2 Bev for protons. This is consistent with the results of an analysis by Neher[3] in terms of the energy flux brought in by the primary cosmic radiation.

Hilberry's[4] earlier measurements on extensive showers as well as more recent underground experiments[5] indicated that the exponent in a simple power-law spectrum is higher at higher energies. It has also been demonstrated that a marked departure occurs at the low-energy end of the spectrum.[6] Therefore, despite the fact that the data obtained at different latitudes on the average appeared to be adequately represented by a straight line on a log-log plot of intensity *vs* threshold energy, the possibility of deviations from this general gross behavior was not precluded. As a matter of fact, vertical coincidence measurements obtained in India by Neher and Pickering[7] in 1939–40 had revealed no difference between the intensity-depth curves at 3° N and 17° N, a result which was then regarded as direct evidence for a banded structure in the primary cosmic-ray spectrum as predicted by the atom-annihilation hypothesis for the origin of cosmic rays proposed by Millikan, Neher, and Pickering.[8] A systematic program of balloon flights with the same standardized equipment which had previously been extensively utilized at higher latitudes[9] was therefore undertaken near the geomagnetic equator not only to determine whether this condition still prevails, but also to examine in some detail the energy dependence of various properties of the primary cosmic rays.

## II. EXPERIMENTAL PROCEDURE

The data reported in the present paper were obtained in India during the series of balloon flights summarized in Table I. The ascents were conducted during three periods, initially at Aligarh, Uttar Pradesh (geomagnetic latitude 18° N), next at Bangalore, Mysore (geomagnetic latitude 3° N), and finally, again at Aligarh. The experiments were performed with quadruple-coincidence counter trains in two different geometrical arrangements designated $A$ and $B$. These were utilized to obtain, as a function of atmospheric depth, measurements of the intensity of those cosmic-ray particles at very high altitudes having a minimum residual range of 4.0 cm, 7.5 cm, or 17.7 cm of Pb, respectively. The general techniques have previously been described in detail.[10] Numerous measurements had already been

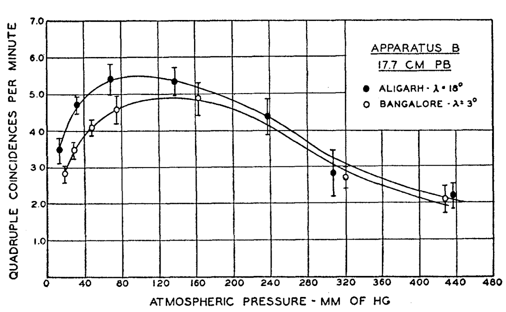


FIG. 3. Variation of counting rate with atmospheric pressure, for particles traversing 17.7 cm of Pb.

[1] Winckler, Stix, Dwight, and Sabin, Phys. Rev. **79**, 656 (1950).
[2] J. A. Van Allen and S. F. Singer, Phys. Rev. **78**, 819 (1950).
[3] H. V. Neher, *Progress in Cosmic Ray Physics* (North Holland Publishing Company, Amsterdam, 1952), p. 301.
[4] N. Hilberry, Phys. Rev. **60**, 1 (1941).
[5] Barrett, Bollinger, Cocconi, Eisenberg, and Greisen, Revs. Modern Phys. **24**, 133 (1952).
[6] For a discussion of this matter see, e.g., M. A. Pomerantz and G. W. McClure, Phys. Rev. **86**, 542 (1952).
[7] H. V. Neher and W. H. Pickering, Phys. Rev. **61**, 407 (1942).
[8] Millikan, Neher, and Pickering, Phys. Rev. **61**, 397 (1942).
[9] Reference 6, and earlier publications cited therein.
[10] M. A. Pomerantz, Electronics **24**, 88 (1951).

obtained[9] at high altitudes with type $A$ at Churchill, Manitoba (geomagnetic latitude 69° N) and with both types at Swarthmore, Pennsylvania (geomagnetic latitude 52° N), as well as in the lower atmosphere.[11] The geometrical factors[12] whereby all counting rates in the accompanying curves may be reduced to absolute unidirectional intensities are summarized in Table II.

## III. RESULTS AND DISCUSSION

### A. Intensity *vs* Altitude Curves

Intensity *vs* altitude curves were obtained with vertical quadruple-coincidence counter trains of Type $A$ containing 4.0 cm Pb and 7.5 cm Pb, respectively, and Type $B$ containing 17.7 cm Pb. The data obtained in separate flights were in satisfactory agreement. The composite results, obtained by combining all of the data for a specific altitude interval during both ascent and descent of the several individual instruments, are plotted in Figs. 1, 2, and 3.

The most striking result, which is immediately apparent in all cases, is that a rather pronounced latitude effect occurs between 18° N and 3° N. Furthermore, each of the curves exhibits a distinct maximum which does not appear at high latitudes when the interposed absorber exceeds approximately 5 cm of Pb.

As is seen in Fig. 1, in the equatorial region the intensity of particles having a residual range exceeding 4 cm of Pb is maximum at an atmospheric depth of approximately 100 mm of Hg. Previous experiments had indicated that at 52° N the maximum occurs at 50 mm of Hg, whereas at 69° N the curve flattens off at low pressures. These observations are in accord with the expectation that an increase in the low-energy limit of the primaries is accompanied by an increase in the amount of interposed absorber required to remove the maximum in the total vertical intensity *vs* altitude curve. Moreover, it is not surprising that the maximum in the atmospheric transition curve shifts towards the top of the atmosphere as the average energy of the primaries is reduced.

The maximum with 7.5 cm of Pb interposed in the counter train is rather flat in the vicinity of 80 mm of Hg (Fig. 2). At the higher latitudes, in contrast, the intensity increases monotonically with altitude. Although conflicting conclusions regarding the latter point had appeared,[13] the recent experiments of Pullar and Dymond[14] have unambiguously confirmed this result and have resolved this question.[15]

A peak is also present in the intensity-depth curve of particles which can penetrate at least 17.7 cm of Pb, again representing an appreciable change from the

[11] M. A. Pomerantz, Phys. Rev. **75**, 1721 (1949).
[12] Reference 11 contains a complete discussion of these factors.
[13] M. L. Vidale and M. Schein, Phys. Rev. **81**, 1065 (1951); M. Vidale, *ibid.* **88**, 266 (1952).
[14] J. D. Pullar and E. G. Dymond, Phil. Mag. **44**, 565 (1953).
[15] E. G. Dymond in *Progress in Cosmic Ray Physics* (North Holland Publishing Company, Amsterdam, 1954), Vol. 2, Chap. 3.

TABLE I. Balloon-flight summary.

| Flight No. | Date | Station | Absorber, cm Pb | Zenith angle | Ceiling altitude, feet |
|---|---|---|---|---|---|
| 2 $A$ | 12–28–52 | Aligarh | 7.5 | 0° | 88 000 |
| 3 $A$ | 12–31–52 | Aligarh | 7.5 | 0° | 85 000 |
| 4 $A$ | 1– 8–53 | Aligarh | 7.5 | 0° | 85 000 |
| 5 $A$ | 1–18–53 | Aligarh | 7.5 | 0° | 102 000 |
| 6 $A$ | 3–25–53 | Bangalore | 7.5 | 0° | 87 000 |
| 7 $A$ | 3–27–53 | Bangalore | 7.5 | 0° | 51 000 |
| 8 $A$ | 3–30–53 | Bangalore | 7.5 | 0° | 88 000 |
| 9 $A$ | 4– 2–53 | Bangalore | 7.5 | 0° | 90 000 |
| 10 $A$ | 4–13–53 | Bangalore | 7.5 | 90° | 89 000 |
| 11 $A$ | 4– 7–53 | Bangalore | 7.5 | 90° | 78 000 |
| 12 $A$ | 5– 5–53 | Bangalore | 4.0 | 0° | 86 000 |
| 13 $A$ | 5– 6–53 | Bangalore | 4.0 | 0° | 98 000 |
| 14 $A$ | 5–28–53 | Aligarh | 4.0 | 0° | 83 000 |
| 15 $A$ | 5–27–53 | Aligarh | 4.0 | 0° | 70 000 |
| 17 $A$ | 6– 6–53 | Aligarh | 4.0 | 0° | 95 000 |
| 1 $B$ | 1–29–53 | Aligarh | 17.7 | 0° | 85 000 |
| 2 $B$ | 3– 3–53 | Aligarh | 17.7 | 0° | 100 000 |
| 3 $B$ | 3–31–53 | Bangalore | 17.7 | 0° | 84 000 |
| 4 $B$ | 5– 2–53 | Bangalore | 17,7 | 0° | 80 000 |

behavior at 52° N. The slope near the "top of the atmosphere" is actually greater in this case than with the smaller thicknesses of absorber. The counting rates in Fig. 3 are not directly comparable with those in Figs. 1 and 2, but may be normalized by the factors listed in Table II.

Inasmuch as a coincidence train containing 203 g cm$^{-2}$ of Pb counts predominantly protons having energies exceeding $E=4.5\times10^8$ ev and mesons with energies greater than $2.6\times10^8$ ev, the computations of Messel[16] on the development of the nucleon cascade may be utilized to determine the meson intensity throughout the upper atmosphere. Assuming a primary proton power-law spectrum with $\gamma=1.1$, Messel has calculated the vertical intensity of protons with energy greater than $E$ for various values of the ratio $E_c/E$ (where $E_c$= geomagnetic cut-off energy) as a function of atmospheric depth. In Fig. 4 are plotted the curves $H(\lambda)$ representing the observed vertical intensity penetrating 203 g cm$^{-2}$ of Pb at 3° N and at 52° N, as well as the corresponding theoretical curves $P(\lambda)$ for protons, from Messel's theory. For the present purposes, the simplifying approximation is made that the extrapolated intensity at the "top of the atmosphere" consists

TABLE II. Geometrical factors for converting counting rates to absolute particle intensities. $p$ is defined by: $I(\theta,h,t)=I(0,h,t)\times\cos^p\theta$; $h$ represents atmospheric depth, $t$ thickness of interposed absorber.

| Instrument | Effective length, $l$ cm | Effective width, $w$ cm | Separation, $L$ cm | $\varphi=N(0,h,t)/I(0,h,t)$ $p=2$ | $p=1$ | $p=0$ |
|---|---|---|---|---|---|---|
| $A$ | 19.4 | 0.9 | 11.5 | 1.23 | 1.29 | 1.45 |
| $B$ | 19.4 | 2.3 | 26.6 | 2.33 | 2.50 | 2.52 |
| $\varphi_B/\varphi_A$ | | | | 1.90 | 1.94 | 1.74 |

[16] H. Messel in *Progress in Cosmic Ray Physics* (North Holland Publishing Company, Amsterdam, 1954), Vol. 2, Chap. 4.

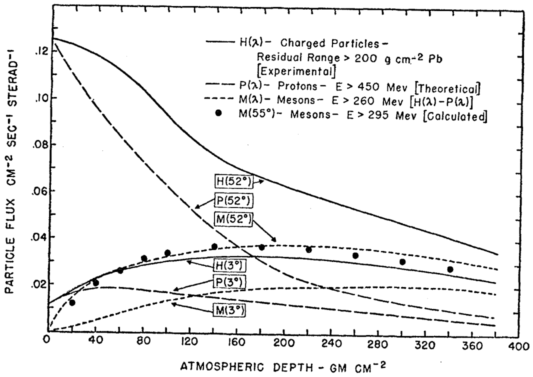


FIG. 4. Particle flux as a function of atmospheric depth at 52° N and 3° N. $H(\lambda)$ represents the total hard component penetrating 203 g cm$^{-2}$ of Pb, $P(\lambda)$ is obtained from Messel's theory of the nucleon cascade (see reference 16), and $M(\lambda)$ is the difference between them, consisting principally of mesons having energies above 260 Mev. The black dots indicate the calculated meson flux at 55° N as derived by Clark from Sands' production spectrum (see reference 19).

exclusively of primary protons at both latitudes. The general features would not be greatly modified by a detailed analysis which, in any event, could not be undertaken at present in view of limitations imposed by both theoretical and experimental considerations.

The approximate intensity of mesons having energies exceeding 260 Mev, $M(\lambda)$, is obtained by subtracting $P(\lambda)$ from $H(\lambda)$. Although the meson curves at 52° N and 3° N both display quite flat maxima, the intensity increases much more rapidly with atmospheric depth at the higher latitude, where the average primary energy is lower. The proton and meson intensities are equal at 165 g cm$^{-2}$ at 52° N, and 122 g cm$^{-2}$ at 3° N. There is striking agreement between the $M(52°)$ curve and the points derived from Sands[17] production spectrum by Clark.[18] Clark's proton curves, which when added to the computed meson and alpha-particle curves yield the counting rates observed in his investigations of the hard component (divided experimentally into two groups according to whether or not the traversing particle produced a nuclear interaction in the absorber, thereby triggering side counters), however, lead to a net result for protons having energies exceeding 0.5 Bev which lies above $P(52°)$ plotted in terms of the present data. This arises from the fact that Clark's values of the flux penetrating 20 cm of Pb in the upper atmosphere at 55° N are about 50 percent higher than those indicated by curve $H(52°)$, although they coincide at lower altitudes. A similar trend is indicated in related measurements of the total intensity.[19] It should be emphasized that these considerations do not apply to the predicted meson curve, which does not involve balloon-flight data.

On the other hand, the *shape* of the curve representing the total intensity of protons with $E>0.5$ Bev, deduced from Clark's analysis, is in excellent agreement with $P(\lambda)$ as given by Messel.

Using Messel's earlier computations based upon $\gamma=1.7$, Pullar and Dymond[14,15] derived the meson flux from measurements of the hard component (range$>90$ g cm$^{-2}$ Pb) at high latitudes. If the corresponding calculations were applied to the present equatorial data, the theoretical proton curve would actually exceed the observed hard component curve (Fig. 2). The maximum counting rate due to protons alone would be 3.3 at 100 mm of Hg, as compared with the observed rate of 2.9 counts per minute which includes both protons and mesons. In contrast, the revised theory with $\gamma=1.1$ would doubtless provide a reasonable result from this qualitative point of view, although the detailed calculations with the parameters applicable to this set of conditions have not been performed.

### B. Absolute Primary Flux

In Table III are listed values of the absolute particle flux near the geomagnetic equator, as reported by various investigators. The intensity at balloon altitude measured by Winckler *et al.* (W, 3 cm Pb, 15 g/cm²) and the present author (P, 4 cm Pb, 10 mm Hg) are in

TABLE III. Absolute vertical intensity measurements near geomagnetic equator.

| Geomagnetic latitude | Particle flux, cm$^{-2}$ sec$^{-1}$ sterad$^{-1}$ | Author[a] | Absorber | Atmospheric depth |
|---|---|---|---|---|
| 0° | 0.027±0.001 | W | 3 cm Pb | 15 g/cm² |
| 0° | 0.031±0.001 | W | 0 | 15 g/cm² |
| 0° | 0.021±0.001 | W | 3 cm Pb | Top-extrapolated |
| 0° | 0.028±0.004 | V | 0 | Rocket |
| 3° | 0.0227 | R | 10 cm Pb | Top-extrapolated |
| 3° | 0.029±0.002 | P | 4 cm Pb | 10 mm Hg |
| 3° | 0.028±0.002 | P | 7.5 cm Pb | 20 mm Hg |
| 3° | 0.025±0.001 | P | 4 cm Pb | Top-extrapolated |
| 3° | 0.024±0.001 | P | 7.5 cm Pb | Top-extrapolated |
| 19° | 0.0364 | R | 10 cm Pb | Top-extrapolated |
| 20° | 0.031±0.001 | W | 3 cm Pb | 15 g/cm² |
| 20° | 0.024±0.001 | W | 3 cm Pb | Top-extrapolated |
| 18° | 0.039±0.002 | P | 4 cm Pb | 10 mm Hg |
| 18° | 0.036±0.002 | P | 7.5 cm Pb | 20 mm Hg |
| 18° | 0.034±0.001 | P | 4 cm Pb | Top-extrapolated |
| 18° | 0.032±0.001 | P | 7.5 cm Pb | Top extrapolated |

| Latitude ratio | Author | Absorber | Atmospheric depth |
|---|---|---|---|
| $I(19°)/I(3°)=1.60$ | R | 10 cm Pb | Top-extrapolated |
| $I(20°)/I(0°)=1.15$ | W | 3 cm Pb | 15 g/cm² |
| $I(20°)/I(0°)=1.14$ | W | 3 cm Pb | Top-extrapolated |
| $I(18°)/I(3°)=1.28$ | P | 4 cm Pb | 10 mm Hg |
| $I(18°)/I(3°)=1.29$ | P | 7.5 cm Pb | 20 mm Hg |
| $I(18°)/I(3°)=1.39$ | P | 4 cm Pb | Top-extrapolated |
| $I(18°)/I(3°)=1.37$ | P | 7.5 cm Pb | Top-extrapolated |
| $I(52°)/I(3°)=7.1$ | P | 7.5 cm Pd | Top-extrapolated |

[a] These references are as follows. W: Winckler, Stix, Dwight, and Sabin, Phys. Rev. **79**, 656 (1950); V: J. A. Van Allen and A. V. Gangnes, Phys. Rev. **78**, 50 (1950); R: Rao, Balasubrahmanyan, Gokhale, and Pereira, Phys. Rev. **91**, 764 (1953); P: Present author.

[17] M. Sands, Technical Report No. 28, Laboratory of Nuclear Science and Engineering, Massachusetts Institute of Technology, 1949 (unpublished).
[18] M. A. Clark, Phys. Rev. **87**, 87 (1952).
[19] M. A. Clark, Technical Report No. 59, Laboratory of Nuclear Science and Engineering, Massachusetts Institute of Technology, 1952 (unpublished).

agreement, although the value at the "top of the atmosphere" obtained by extrapolation[20] appears to be slightly higher in the latter case. The rocket determination by Van Allen and Gangnes is also in accord within the statistical uncertainties, as is the extrapolated value reported by Rao *et al.*

The situation at 18° is somewhat different, however, and the present result (P, 4 cm Pb, 10 mm Hg) is considerably higher than Winckler's (W, 3 cm Pb, 15 g/cm$^2$) at ceiling altitude at 20°. This difference is increased by extrapolation to zero pressure. The corresponding extrapolated flux measurement by Rao *et al.* at 19° is even higher.

It is of interest to note that, insofar as it is meaningful to compare absolute flux determinations by different investigators, the measurements over India (P, R) differ from those over the Pacific Ocean (W, V) in a sense which is in accord with that theoretically expected to arise from the eccentricity of the terrestrial dipole. As a consequence of the fact that the dipole which represents the earth's magnetic field is off-center, the minimum momentum required for a primary to reach the earth in the vertical direction at 3° in India should be slightly less than that at the geomagnetic equator in the area where Winckler conducted his flights, and higher than that in the region where the rocket was fired. However, Millikan and Neher's world survey[21] revealed that the minimum intensity at sea level does not coincide with the region of maximum threshold energy determined by these considerations, but occurs about 65° west of this position, close to the point at which the horizontal component of the real magnetic field at the surface of the earth is maximum. The intensity at sea level at the geomagnetic equator is actually slightly lower in India than in the Western Hemisphere.

### C. Primary Energy Spectrum

The most frequently quoted expressions relating the latitude dependence of the measured vertical intensity to the corresponding cutoff determined from geomagnetic theory are listed in Table IV. The exponents indicated represent the present series of determinations of the flux at the "top of the atmosphere" as listed in Table III.

TABLE IV. Summary of power-law expressions based upon data obtained at 52° N and 3° N.

| Variable | Geomagnetic cutoff[a] | | Integral spectral distribution |
|---|---|---|---|
| | $\lambda=52°$ | $\lambda=3°$ | |
| Magnetic rigidity, $pc/Ze$ | 2.1 Bv | 15.4 Bv | $N(>pc/Ze)=0.68(1+pc/Ze)^{-1.2}$ <br> $N(>pc/Ze)=0.37(pc/Ze)^{-1.0}$ |
| Proton energy, $E_p$ | 1.4 Bev | 14.2 Bev | $N(>E_p)=0.46(1+E_p)^{-1.1}$ <br> $N(>E_p)=0.23(E_p)^{-0.9}$ |
| Energy per nucleon ($A=2Z$), $E/A$ | 0.4 Bev | 6.8 Bev | $N(>E/A)=0.26(1+E/A)^{-1.21}$ |

[a] Obtained by applying theoretical factors taking into account the asymmetry of the earth's dipole to the values given by R. A. Alpher, J. Geophys. Research **55**, 437 (1950).

TABLE V. Differential magnetic rigidity distributions based upon data obtained at 18° N and 3° N.

| Limiting cone | Geomagnetic cutoff, $pc/Ze$ | | Differential spectral distribution |
|---|---|---|---|
| | $\lambda=18°$ | $\lambda=3°$ | |
| Main cone | 13.8 Bv | 15.4 Bv | $dN(pc/Ze)=k(1+pc/Ze)^{-4.0}d(pc/Ze)$ |
| Störmer +earth's shadow cone | 12.6 Bv | 15.4 Bv | $dN(pc/Ze)=k(1+pc/Ze)^{-2.7}d(pc/Ze)$ |

Analysis of the geomagnetic effects is independent of the composition of the primary cosmic radiation when the cutoffs are expressed in terms of magnetic rigidity, $pc/Ze$, which is therefore the most relevant quantity for the present purposes. At the geomagnetic equator and at latitudes above 35° the lower limit is effectively defined by the Störmer plus earth's shadow cones which determine the least rigidity a charged particle must possess to be allowed to enter from a given direction. In the intermediate region there exists a penumbral region between this lower limit and that value of rigidity determined by the main cone, which if exceeded assures admission. The region about geomagnetic latitude 18° is characterized by great uncertainty regarding the contribution of the penumbral region. The statement is usually made that the penumbral region is practically dark at latitudes below about 15°, so that the main cone is essentially the total allowed cone.[22] Between 15° and 35°, the allowed and forbidden regions of the penumbra are presumed to be of equal importance, but quantitative predictions are exceedingly difficult to propound. Detailed theoretical investigation[23] has indicated that at 20°, the main cone is still quite important in determining the minimum rigidity which is permitted to enter in the vertical direction. It is not possible to predict the contribution of the penumbral region to the cosmic-ray intensity at 18° in India. However, it is not expected to be appreciable.[24] Thus, the value of the exponent, $(\gamma+1)$, in the differential magnetic-rigidity distribution (Table V) is $-4.0$ in the interval $pc/Ze=13.8$–$15.4$ Bv as compared with $-2.2$ averaged over the range between 2.1 Bv and 15.4 Bv, and there appears to be a departure from the assumed simple power law. This might be accounted for by the presence of a considerable flux of particles having energies less than that defined by the main cone. This would have to be attributed to a difference in the contributions from trapped orbits and albedo at different latitudes in India, which apparently does not occur at the longitudes where Winckler's flights were conducted. On the other hand, the form of the primary

[20] Extrapolated values were not specifically stated in reference W of Table III, but have been derived by the present author from the published data.

[21] R. A. Millikan and H. V. Neher, Phys. Rev. **50**, 15 (1936).

[22] M. S. Vallarta, Phys. Rev. **74**, 1837 (1948).

[23] R. A. Hutner, Phys. Rev. **55**, 614 (1939).

[24] M. S. Vallarta (private communication).

spectrum itself might be the origin of the observed effect. If this is the case and if the generally accepted geomagnetic theory is employed to determine the cutoff at the various stations, there remains a discrepancy between the absolute flux measurements at 18° in India and 20° in the Pacific Ocean.

### D. Absorption Coefficients

Comparison of the data obtained with different thicknesses of absorber interposed in the counter train reveals the manner in which the absorption of the cosmic radiation at high altitudes depends upon the energy of the incoming particles. The curves in Fig. 5 indicate the general trends which are followed, although their precise shapes are not significant owing to the statistical uncertainties entering into the differences between counting rates. The greatest absorption of the softer components (residual range between 4.0 and 7.5 cm Pb) occurs deeper in the atmosphere at low latitudes where the average primary energy is higher. Furthermore, at low latitudes the more penetrating component (17.7 cm Pb>range>7.5 cm Pb) appears to be hardening as it proceeds downward into the atmosphere, contrary to the situation at high latitudes.

The effective absorption length in lead, determined from the data obtained with the larger amounts of interposed absorber, is about 290 g $cm^{-2}$ at 52°, 18°, and 3°. Thus, the interaction mean free path does not change when the energy of the primary protons is increased from 1.4 Bev to 14.2 Bev.

The variation in the atmosphere of the new radiation which appears between 3° and 18° is similarly represented by differences as shown in Fig. 6. These curves show the altitude dependence of the intensity of the incoming particles and their progeny capable of penetrating 4.0 cm Pb, 7.5 cm Pb, and 17.7 cm Pb, respectively, which are present at 18° but not at 3°.

### E. Horizontal Intensity

Flights with counter trains oriented horizontally were conducted only at Bangalore, and the results are plotted in Fig. 7. The bump at about 75 mm of Hg repeated consistently and appears to represent a real phenomenon, despite the fact that one is hesitant to attach significance to apparent fine structure in intensity-depth curves of this type.

The altitude variation of the ratio of horizontal to vertical intensities is shown in Fig. 8. It is quite remarkable that this factor is almost the same, at the highest altitude attained, at 52° and 3°. The latitude effect of the horizontal component is almost as great as that of the vertical. The bump at 75 mm Hg can probably be ascribed to air showers, which undoubtedly contribute considerably to the counting rate of this arrangement, especially at such depths.

Earlier experiments had revealed no difference in the horizontal intensity between 52° N and 69° N, and this result was interpreted as an indication that low-energy primaries (i.e., near the geomagnetic cutoff at 52°) do not contribute appreciably to the horizontal intensity. As has been noted previously,[6] the particles recorded at high altitudes by a coincidence counter train inclined at a zenith angle of 90° are predominantly secondaries produced by essentially downward-moving primaries. If the more energetic primaries were more efficacious in producing horizontally-directed secondaries, the horizontal/vertical ratio should be higher at 3° N than at 52° N. Thus, the present measurements indicate that the multiplicity for production of wide-angle events is independent of energy for protons between 1.4 Bev and 15.5 Bev, in contrast with the conclusion based upon the northern experiments. This constitutes a dilemma.

## IV. CONCLUSIONS

The existence of a large variation with latitude of the primary cosmic-ray intensity between 3° N and 18° N in India has been established, although the explanation for earlier observations to the contrary is not clear. Although appreciable fluctuations in the intensity of low-energy particles are sometimes ob-

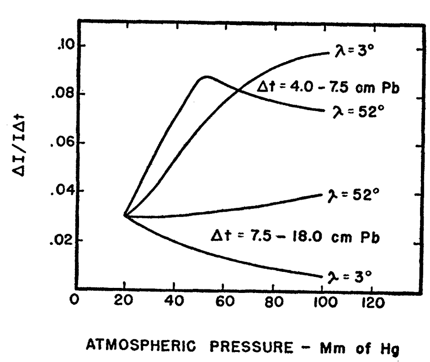


FIG. 5. Variation with atmospheric pressure, at 3° N and 52° N, of the absorption coefficient of two groups of cosmic rays, having residual ranges of 4.0–7.5 cm of Pb and 7.5–18.0 cm of Pb, respectively.

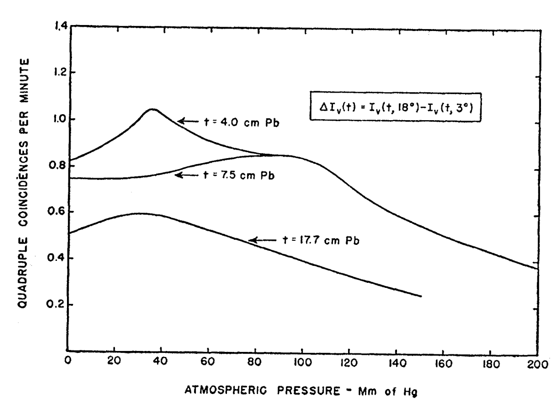


FIG. 6. Counting rate *vs* atmospheric pressure, for particles (having ranges exceeding 4.0 cm of Pb, 7.5 cm of Pb and 17.7 cm of Pb, respectively) which are present in India at 18° N but not at 3° N.

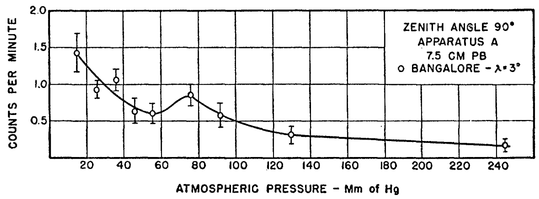


FIG. 7. Horizontal counting rate as a function of atmospheric pressure for cosmic rays penetrating 7.5 cm of Pb at 3° N.

served[25,26] at high altitudes, time variations in the intensity of particles having rigidities exceeding the geomagnetic cutoff in the equatorial regions are presumably much smaller.[26]

The intensity-depth curves, as well as the absorption characteristics of the cosmic rays at high altitudes, are in accord with expectation in terms of the change with latitude of the average energy of the primaries. The nucleon cascade theory developed by Messel appears to be in harmony with the experimental results.

The latitude effect observed in India is greater than that expected on the basis of the customary assumptions and reliance on standard geomagnetic theory. This may be indicative of the nature of the spectrum at the upper limit of the field-sensitive region for vertical incidence; alternatively, the possibility of local magnetic anomalies or contributions from trapped orbits and albedo must be considered. Unless very special conditions prevail the latter explanation does not appear tenable, particularly in view of the results of the beautiful experiments reported recently by Winckler and Anderson.[27] Utilizing a Čerenkov detector, they determined that, at $\lambda=40°$ N, the albedo is not more than 5 percent of the incident flux, for particles of $\beta>0.7$ in any upward direction. This is too small by a factor of at least four to resolve the discrepancy between the observed east-west asymmetry and that predicted from the primary spectrum and geomagnetic theory. Also, according to new calculations by Treiman,[28] the contribution arising from the trapped orbits of a solar dipole field is appreciably smaller than had been indicated earlier.[29] Moreover, as a consequence of Liouville's theorem, the intensity of trapped particles is constant throughout the accessible bounded volume of space. The irregularity in the spectrum indicated by the present experiments may be related to the aforementioned inconsistency among the other geomagnetic effects.

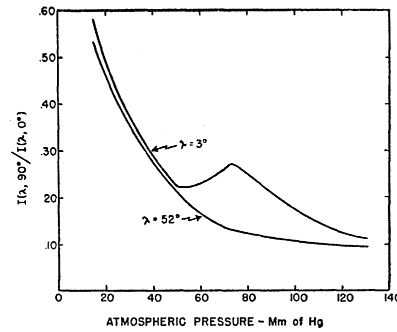


FIG. 8. Ratio of intensity in the horizontal direction to that in the vertical direction at 52° N and 3° N, as a function of atmospheric pressure.

The intensity in the horizontal direction does not exhibit as much latitude variation as would have been anticipated from qualitative considerations involving the observations at northern latitudes. Thus, a simple picture of this phenomenon is inadequate to account for the observed results.

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[25] M. A. Pomerantz and G. W. McClure, Phys. Rev. **87**, 240 (1952).
[26] Neher, Peterson, and Stern, Phys. Rev. **90**, 655 (1953).
[27] J. R. Winckler and K. Anderson, Phys. Rev. **93**, 596 (1954).
[28] S. B. Treiman, Phys. Rev. **93**, 544 (1954).
[29] Kane, Shanley, and Wheeler, Revs. Modern Phys. **21**, 51 (1949).