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The Determination of the Sign and the Energy Spectrum of Primary Cosmic Radiation*

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An experiment is reported in this paper for the measurement of the complete azimuthal effect. This experiment was performed in Mexico City (geomagnetic latitude 29°, altitude 2242 m above sea level) for constant zenith angles 20°, 40°, and 60°. A characteristic feature is that the length of the atmospheric path is constant, hence the assumption is made that the number of secondaries detected by the cosmic-ray telescope is a measure of the number of primaries. The analysis yields an energy spectrum of the primary radiation of the form $K/E^{1.45}$ (E = energy, K = constant). There is no evidence of negative primary particles. The results are subject to revision because the penumbra bands at this latitude are only imperfectly known, and also because of the resolving power of our present apparatus. The possibility of a bright line spectrum, or of such a spectrum superimposed on a continuous distribution, is not ruled out. The possibility of negative primaries is excluded within the limits of experimental error. The spectrum obtained from our experimental data agrees completely with that determined from the experiment of Gill, carried out at Lahore, Punjab, India. The result is valid in the energy range from about 350 to 600 millistörmers, or 6 to 21 Bev if the primaries are protons.

1. INTRODUCTION

It has been repeatedly pointed out in the literature that, in principle, the earth is a good magnetic spectrograph suitable for the determination of the energy spectrum of primary cosmic radiation. Several experiments can be suggested with this end in view, of which the measurement of the total latitude effect and of the north-south effect at different latitudes are two examples. The difficulty about the interpretation of these experiments is that of necessity they must be performed not outside, but inside the earth's atmosphere. The passage of primary cosmic rays through air produces many very complicated phenomena which cannot be excluded. Therefore the first requirement is to devise a type of experiment in which some of the atmospheric effects are removed or at least kept constant. It is well known that many of these effects depend essentially on the length of the atmospheric path, hence it appears desirable to plan an experiment in which this parameter is kept constant.

On the occasion of the Symposium on Cosmic Rays held at the University of Chicago in July, 1939 one of us[1] suggested the measurement of the complete azimuthal effect as an experiment satisfying the condition already mentioned. Since the zenith angle is kept fixed, the length of the atmospheric path is also constant. As a matter of fact such an experiment is also suited to obtain very extensive information on the sign of primary cosmic radiation.

It follows from the theory of the allowed cone of cosmic radiation[2] that, at each point of the earth and for each zenith angle, an experiment of the kind already mentioned explores a certain energy range which decreases continuously from the geomagnetic equator to the pole, and, at a given point, from the horizon to the zenith. The theory of the determination of the energy spectrum from the measurement of the azimuthal effect, taking into account the so-called penumbra bands, has been worked out by R. A. Hutner.[3]

2. DESCRIPTION OF THE EXPERIMENT

The experiment was carried out in Mexico City (geomagnetic latitude 29°, altitude 2242 meters). The apparatus was built by A. Baños, Jr. and M. L. Perusquía, and will be described shortly in the literature.[4] It consists essentially of four trains of Geiger-Müller counters connected so as to record triple coincidences. The counters were made in the laboratory of R. D. Evans at the Massachusetts Institute of Technology, and

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[1] M. S. Vallarta, Rev. Mod. Phys. 11, 239 (1939).
[2] See, for example, M. S. Vallarta, *An outline of the theory of the allowed cone of cosmic radiation* (Univ. of Toronto Press, 1938).
[3] R. Albagli Hutner, Phys. Rev. 55, 15, 614 (1939).
[4] Alfredo Baños, Jr. and M. L. Perusquía, to be submitted to Rev. Sci. Inst.

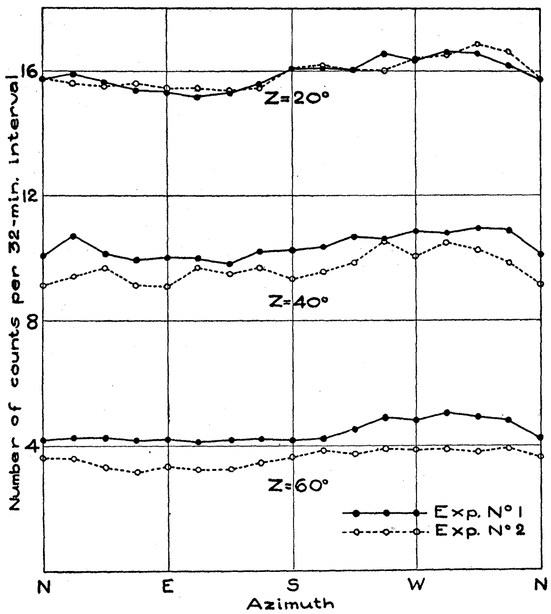

FIG. 1. The experimental azimuthal effect.

were designed specially for high stability over long periods of time. They have proved thoroughly dependable in operation. The trains of counters are placed at zenith angles 0°, 20°, 40°, and 60°, and can be arranged so as to secure best resolution either in zenith angle or in azimuth. The resolving power of each train is 5.5×21.5°. The apparatus rotates about the geomagnetic vertical axis by $\frac{1}{16}$ of a revolution each time, so that each train of counters stays in each azimuth for 32 minutes, and after such an interval the azimuth of each train increases by 22.5°. It is housed in a room built of pressed concrete and fiber boards located on top of a tower. The operation of the apparatus is wholly automatic, and the number of triple coincidences on each of the four trains is recorded photographically at the end of each 32-minute interval. Room temperature is controlled thermostatically at 35°C. Time signals to control the rotation were provided by a master clock at the University Observatory in Tacubaya. In order to secure high precision the apparatus was kept in fairly continuous operation twice for periods of at least 100 days. The first run lasting, with a few interruptions, from July 17, 1943 to September 7, 1944, for a total of 401 days and 32,335 recorded triple coincidences, was made with the counters placed so as to give best resolution in zenith angle; the second, including, with some interruptions, the period from October 21, 1945 to May 19, 1946, for a total of 137 days and 10,546 recorded triple coincidences, was made with the counters placed so as to give best resolution in azimuth.

3. STATISTICAL ANALYSIS

For each azimuth and each zenith angle a statistical analysis was carried out of the frequency distribution of triple coincidences recorded by each train, on the basis of intervals of 32 minutes. The mean value of the number of triple coincidences per interval was calculated from the formula

$$\bar{x} = \sum xf_x/n,$$

TABLE I. Azimuthal effect, experiment No. 1.

Zenith distance	20°		40°		60°	
Azimuth	Mean value	Probable error	Mean value	Probable error	Mean value	Probable error
N	15.74	0.12	10.07	0.09	4.22	0.07
N N E	15.94	0.12	10.76	0.09	4.27	0.07
N E	15.69	0.11	10.16	0.09	4.28	0.06
E N E	15.40	0.11	9.94	0.09	4.18	0.06
E	15.35	0.11	10.01	0.09	4.22	0.06
E S E	15.19	0.11	10.00	0.09	4.13	0.06
S E	15.30	0.11	9.85	0.10	4.19	0.06
S S E	15.58	0.11	10.21	0.09	4.23	0.06
S	16.03	0.12	10.28	0.09	4.20	0.06
S S W	16.07	0.11	10.37	0.10	4.25	0.07
S W	16.01	0.11	10.73	0.09	4.56	0.07
W S W	16.57	0.11	10.65	0.09	4.91	0.07
W	16.34	0.11	10.88	0.10	4.82	0.07
W N W	16.62	0.11	10.85	0.09	5.05	0.07
N W	16.59	0.12	10.99	0.09	4.92	0.07
N N W	16.18	0.12	10.94	0.09	4.82	0.07

TABLE II. Azimuthal effect, experiment No. 2.

Zenith distance	20°		40°		60°	
Azimuth	Mean value	Probable error	Mean value	Probable error	Mean value	Probable error
N	15.76	0.19	9.15	0.26	3.66	0.10
N N E	15.63	0.18	9.45	0.20	3.64	0.09
N E	15.55	0.16	9.72	0.25	3.32	0.07
E N E	15.65	0.18	9.13	0.25	3.17	0.08
E	15.45	0.16	9.11	0.26	3.36	0.09
E S E	15.48	0.18	9.71	0.26	3.25	0.07
S E	15.38	0.18	9.51	0.22	3.28	0.07
S S E	15.44	0.19	9.73	0.24	3.48	0.08
S	16.06	0.20	9.34	0.18	3.64	0.09
S S W	16.18	0.19	9.57	0.24	3.89	0.09
S W	16.01	0.18	9.89	0.26	3.74	0.09
W S W	16.00	0.17	10.59	0.28	3.91	0.09
W	16.38	0.12	10.06	0.28	3.89	0.07
W N W	16.53	0.12	10.54	0.28	3.90	0.09
N W	16.88	0.18	10.30	0.25	3.81	0.10
N N W	16.63	0.18	9.89	0.24	3.94	0.09

TABLE III. East-west, A_w, and north-south, A_s, asymmetries.

Zenith angle → Asymmetry		20°	40°	60°
A_w	Exp. 1	0.063	0.083	0.134
A_w	Exp. 2	0.058	0.099	0.144
A_s	Exp. 1	0.018	0.021	0
A_s	Exp. 2	0.019	0.021	0

where n is the number of intervals and f_x the frequency of occurrence of the value x. The probable error was calculated from

$$\text{P.E.}(\bar{x}) = 0.67449\sigma/(n)^{\frac{1}{2}}$$

where σ is the standard deviation. For each analysis the x^2-test was made with a discontinuous variable distribution governed by Poisson's law, and the first four coefficients of a Gram-Charlier type B series expansion were obtained. As a final result the adopted mean value of the number of coincidences for each analysis was

$$m = \bar{x} \pm \text{P.E.}(\bar{x})$$

with a limit of perhaps three times the probable error.

The experimental results for the complete azimuthal effect are given in Tables I and II, and in Fig. 1, on the basis of 32-minute intervals.

4. THE NORTH-SOUTH AND EAST-WEST ASYMMETRIES

Particular attention should be paid to the north-south and east-west asymmetries, defined by $A_S = 2(I_S - I_N)/(I_S + I_N)$ and $A_W = 2(I_W - I_E)/(I_W + I_E)$ respectively. They can be readily computed from Tables I and II, and are given in Table III.

These values should be compared with those obtained previously at the same place by Alvarez and Compton,[5] by Johnson[6] and by Schremp and Baños.[7] It will be seen that the agreement is satisfactory. The values of these asymmetries, calculated from the energy spectrum determined in this paper, are given in a later section.

[5] Luis W. Alvarez and A. H. Compton, Phys. Rev. **43**, 835 (1933).
[6] T. H. Johnson, Phys. Rev. **47**, 91 (1935); ibid. **48**, 287 (1935).
[7] E. J. Schremp and A. Baños, Jr., Phys. Rev. **58**, 662 (1940).

TABLE IV. Values of the lower limit of integration, $E_{\alpha z}$.

Zenith angle	Azimuth	E (main cone) (mS)	E (penumbra) (mS)
20°	N W	400	380
20°	N E	450	430
40°	N W	385	365
40°	N E	500	480
60°	N W	366	345
60°	N E	580	560

5. THE ENERGY LIMITS

We now turn our attention to the main purpose of this paper: the determination of the energy spectrum of the primary cosmic radiation. The intensity in a given direction, defined by the azimuth α and the zenith angle z, is given by

$$I(\alpha, z) = \int_{E(\alpha, z)}^{\infty} F(E)dE,$$

where $F(E)$ is the energy spectrum and E the energy. The lower limit $E(\alpha, z)$ is given by the theory of the allowed cone, and of course depends on the location and size of the penumbra bands. The penumbra has been fairly completely studied at latitudes near the equator by Tchang Yong-Li[8] and at latitudes up to about 20° by R. Albagli Hutner.[3] No such detailed analysis is yet available for higher latitudes, but from general principles already stated by Schremp[9] and by Albagli Hutner,[3] as well as from the knowledge of the shadow cone obtained by the former,[10] it is possible to determine with fair approximation, which however is subject to revision, the penumbra at 29°, the latitude at which the experiment reported in this paper was performed. It is planned to make a detailed study of the penumbra at this latitude with the help of the new differential analyzer at the Massachusetts Institute of Technology. The results of this work will be reported later. It may be necessary at that time to revise the results obtained here.

The main question now is to determine as accurately as possible, on the basis of these considerations, the lower limit of integration $E(\alpha, z)$ for each zenith angle and each azimuth, that is, the least possible value of the energy of a particle

[8] Tchang Yong-Li, Ann. de la Soc. Sci. de Bruxelles **49**, 285 (1939).
[9] E. J. Schremp, Phys. Rev. **54**, 153 (1938).
[10] E. J. Schremp, Phys. Rev. **54**, 158 (1938).

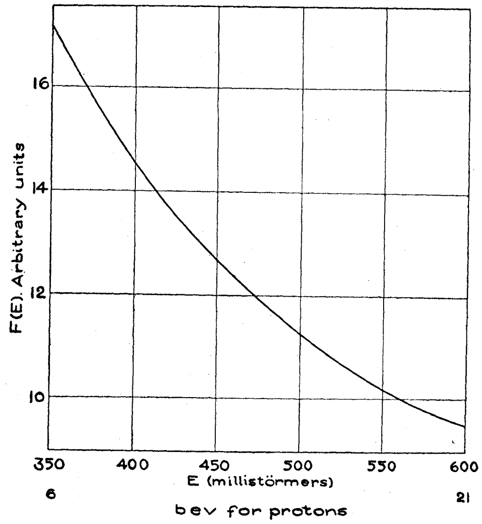

FIG. 2. The energy spectrum.

which can reach the point of observation in the given direction. Typical values thus found are shown in Table IV. These values refer to positive particles and are given in millistörmers (mS). Similar values may be found at other azimuths. Table IV, however, is chosen because it gives the maximum and minimum values of the least energy of arrival. It will be seen from this table that the azimuthal effect at $z=20°$ explores the energy range between 380 and 430 millistörmers, or an interval of 50 mS, that at $z=40°$ it explores between 365 and 480 mS (115 mS), that at $z=60°$ it explores between 345 and 560 mS, or an interval of 215 mS.

6. DETERMINATION OF THE ENERGY SPECTRUM

To determine the spectrum we assume an energy distribution function $F(E)=K/E^c$. We next calculate the intensity $I(z, \alpha)$ using the lower limit of integration $E(z, \alpha)$ obtained as explained in the previous section, and fix the constant K so that the calculated and observed intensities agree at an arbitrarily chosen azimuth, for example the north. To find the exponent c we have, from the discussion above,

$$I(z,\alpha)=\int_{E(z,\alpha)}^{\infty}\frac{K}{E^c}dE=\frac{-K}{c-1}\frac{1}{E(z,\alpha)^{c-1}},$$

therefore

$$-\log\left[\frac{c-1}{-K}I(z,\alpha)\right]=(c-1)\log E(z,\alpha)$$

from which c is determined. A typical calculation is given in Table V. The same value of c is obtained from the other two zenith angles explored, i.e., $z=20°$ and $z=40°$. We therefore conclude that $c=1.45$, and we have the energy distribution function[11] (Fig. 2).

$$F(E)=K/E^{1.45}.$$

A particularly sensitive check of this result is the calculation of the north-south effect. Since the northern and southern boundaries of the allowed cone are only slightly affected by the penumbra, we use the energy limits corresponding to the main cones determined by Lemaitre and Vallarta.[12] The result is shown in Table VI.

7. THE SIGN OF PRIMARY PARTICLES

The question of the sign of the primary particles will now be taken up. From the theory of the allowed cone[13] it is known that the cones for positive and negative particles are symmetrical with respect to the geomagnetic meridian plane. Hence, if there were equal numbers of positive and negative primaries of the same energy, the intensity oscillations due to the penumbra bands should have been symmetrical with respect to the meridian plane; if there were less negatives than positives of the same energy the oscillations should have been asymmetrical as to size, but symmetrical as to position. Finally if the negative primaries had a quite different energy spectrum from the positives, the oscillations on either side

TABLE V. Values of the exponent, c.

Azimuth	$\lambda=29°$ Relative intensity	$z=60°$ $E(z,\alpha)$ (mS)	Exp. N° 2 $-\log\frac{I}{K}(c-1)$	$\log E$	$c-1$
N	1	400	1.1685	2.6021	0.45
N E	0.907	570	1.2109	2.7559	0.44
E	0.918	550	1.2055	2.7404	0.44
S E	0.896	490	1.2162	2.6902	0.45
S	0.995	395	1.1703	2.5966	0.45
S W	1.022	360	1.1590	2.5563	0.45
W	1.063	350	1.1421	2.5441	0.45
N W	1.041	350	1.1511	2.5441	0.45

[11] In our preliminary communication (New York meeting of the American Physical Society, September 1946) a variable exponent c was reported. Our preliminary calculations have been shown since to be incorrect, chiefly because the statistical analysis of the experimental results had not yet been completed.

[12] G. Lemaitre and M. S. Vallarta, Phys. Rev. 49, 719 (1936).

[13] Reference 1, or G. Lemaitre and M. S. Vallarta, Phys. Rev. 50, 493 (1936).

of the meridian should have been quite asymmetrical, but there still should have been intensity oscillations on either side of the meridian plane, and these oscillations should have been related for all zenith angles, i.e., they should have gone with the cones of the same energy. In the present experiment oscillations are quite apparent on the side of the meridian plane belonging to positive particles (i.e., on the north to west and west to south quadrants), but none are significant on the side corresponding to negative primaries, within the limits of experimental error, except perhaps that between the north and east at $z=40°$ (Fig. 1). Hence we conclude that within these limits there are no negative particles in primary cosmic radiation, and that the energy spectrum calculated above is that of positive primaries. This conclusion seems to run against the theory of the origin of cosmic rays suggested by Millikan and his collaborators.[14] Although this theory has not yet been fully worked out it would seem to require equal numbers of positive and negative primaries of the same energy, which is ruled out by the present evidence.

The possibility that the energy spectrum may be discontinuous, perhaps consisting of several bright lines, belonging to positive particles, is not ruled out by the present evidence. We take up this question again in a later section.

8. GILL'S EXPERIMENT

The analysis of the energy spectrum outlined above may be extended to higher energies by using the experimental results of Gill,[15] obtained in Lahore at $\lambda=22°$, at a constant zenith angle $z=60°$. Bearing in mind the longitude effect between Lahore and Mexico City,[16] his experiment takes in the energy range from around 380 to nearly 600 mS, with the added advantage that at his latitude the penumbra bands are much better known from the work of Albagli Hutner.[3] An analysis similar to that outlined above yields exactly the same value for c as that obtained here, i.e., $c=1.45$, in agreement with our result. We therefore conclude that the energy spectrum of the primary rays is

$$F(E)=K/E^{1.45},$$

TABLE VI. North-south effect.

Zenith angle	20°	40°	60°
Energy limits (mS)	420–440	410–430	400–395
A_n calculated	0.0211	0.0212	−0.002
A_n observed	0.018	0.021	0

valid in the range from 350 to 600 mS. If now we make the further assumption that the primary particles are protons, as is made very likely by the work of Schein and his collaborators, we may translate the energy range from Störmers to electron-volts. By using the table given by Lemaitre and Vallarta[17] it is seen that this range is from about 6 to 21 Bev.

9. DISCUSSION

The agreement between the energy spectrum determined from Gill's experiment and from that reported in this paper is particularly encouraging, as they were performed at quite different latitudes, longitudes, and altitudes above sea level. This agreement also lends support to the assumption that, so long as the length of the atmospheric path is constant, the number of secondaries detected by a cosmic-ray telescope in a given zenith angle and azimuth is directly related to the number of primaries incident in the same direction, so that the number of secondaries is a measure of the number of primaries.

As already mentioned earlier, the possibility that the energy spectrum may consist of a number of bright lines in the energy range mentioned before is not altogether excluded by the present experiment. For example, if there were three bright lines at 6.6, 7.5, and 13.2 Bev., belonging to the annihilation of nitrogen, oxygen, and silicon, as suggested by Millikan and his collaborators,[14] we should observe sudden changes of intensity as the direction defined by a cosmic-ray telescope measuring the azimuthal effect cuts across the boundary of the allowed cones corresponding to these energies, i.e., from the southeast around to the northwest at $z=60°$. The oscillations observed in the experiment reported here may be accounted for by a continuous energy distribution and the penumbra bands. However, since the latter are not yet known with sufficient

[14] R. A. Millikan, H. V. Neher, and W. H. Pickering, Phys. Rev. **61**, 397 (1942).
[15] P. S. Gill, Phys. Rev. **67**, 347 (1945).
[16] M. S. Vallarta, Phys. Rev. **47**, 647 (1935).
[17] G. Lemaitre and M. S. Vallarta, Phys. Rev. **43**, 87 (1933), Table VI.

precision, and since the resolving power of our instrument does not allow a sufficiently fine exploration of the interesting region of the sky, the possibility suggested by Millikan *et al.* must for the present remain open. What is definitely disproved by the present experiment is their suggestion of a bright line spectrum symmetrical for positive and negative primary particles.

Finally it should be emphasized that the results reported here may still require further revision as soon as the penumbra bands at the latitude of Mexico City have been well determined. It may also be necessary, in order to settle the question of a bright line energy spectrum, to repeat this experiment using an apparatus with much better resolving power than any used so far for work on cosmic rays. A bright line spectrum superimposed on a continuous background may also be a possibility. At any rate, measurements of the complete azimuthal effect at properly chosen latitudes and with properly designed apparatus, as shown here, are quite able to solve the very important problem of the determination of the energy spectrum and sign of primary cosmic radiation.

Our results do not seem to agree with those of Schremp and Baños.[7] Whether this is ascribable to the limitations imposed by the resolving power of our apparatus or to some other reason is still an open question.*

ACKNOWLEDGMENT

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* *Note added in proof, February 12, 1947.*
It has been suggested to one of us (M.S.V.) by Professors B. Rossi of Massachusetts Institute of Technology and J. R. Oppenheimer of the University of California that negative primary particles, if they are electrons, may be undetected in this experiment because their secondaries generated by a cascade process would be already absorbed by the atmosphere at 2242 m altitude. In order to test this important point it is planned to repeat the present experiment at an altitude of not less than 5000 m.

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Azimuthal Variations of Cosmic Radiation at Lahore

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A study of the azimuthal variations of the cosmic radiation at Lahore (22° N magnetic latitude) shows a large azimuthal effect. The azimuthal effect in the northwest quadrant for a constant zenith angle of 60° is in general agreement with theoretical prediction. These observations lead to the conclusion that (1) primary cosmic-ray particles are positively charged (2) the energy spectrum of the primary cosmic rays within the energy range 7.84×10^9 ev and 14×10^9 ev (for protons) obeys the law $BE^{-\gamma}$ where $\gamma\simeq2.8$.

IN 1940 the author initiated a detailed study of the azimuthal variations of the hard component of cosmic radiation at Lahore (22° N magnetic latitude). Reports on the progress of this work have been published previously.[1] These experiments were planned on the basis of Hutner's[2] calculations of the azimuthal effect of cosmic rays, for a constant zenith angle of 60 degrees, at a geomagnetic latitude of 20 degrees North. Similar studies of the azimuthal variations of cosmic rays have been made by Vallarta, Perusquía, and De Oyarzábal[3] at Mexico City (29° N magnetic latitude). The results obtained

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[1] P. S. Gill, Phys. Rev. **60**, 153 (1941); **67**, 347 (1945); P. S. Gill, Proc. Ind. Acad. Sci. **12**, 53 (1945); P. S. Gill and S. P. Malhotra, Science and Culture **11**, No. 6, 321 (1945).
[2] R. A. Hutner, Phys. Rev. **55**, 15 (1939); **55**, 614 (1939).
[3] M. S. Vallarta, M. L. Perusquía and J. De Oyarzábal, Phys. Rev. **70**, 785 (1946).