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Comparison of the Angular Distributions of the Cosmic Radiation at Elevations 6280 ft. and 620 ft.

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The ray intensity $j(\theta)$ of the cosmic radiation has been studied as a function of the angle θ from the vertical on Mt. Washington, New Hampshire, elevation 6280 ft. and at a base station, elevation 620 ft. The results show a distribution less concentrated about the vertical at the higher elevation. Unless some *ad hoc* assumption is invoked this result is inconsistent with the intensities and absorption coefficients deduced by Millikan and Cameron as their results would lead to a considerably more concentrated distribution at the upper elevation. Integrating the ray intensities over all angles, the total numbers of rays per cm^2 per sec. have been computed at the two elevations. The increase in the number of rays with elevation is less than the known increase in the ionization (Millikan and Cameron). The ratio of numbers of rays per sec. is 1.46 against 1.91 for the ratio of ionizations at the two elevations. The average 6280 ft. ray, therefore, produces 1.31 as many ions per unit path as the 620 ft. ray. This change in ionizing efficiency may perhaps be explained by supposing that the softer rays, which are more predominant at the upper level, produce more secondary rays from the walls of the ionization vessel.

ALTHOUGH the angular distribution of the cosmic radiation at a single elevation has been measured by Bernardini,[1] Medicus,[2] Tuwim,[3] Skobelzyn[4] and others, it is believed that the measurements herein reported are the first to show the changes in this distribution with elevation. The relative intensities of the radiation at various angles from the vertical have been measured on Mt. Washington, New Hampshire, elevation 6280 ft. and at a nearby station in Maine, elevation 620 ft., under conditions such that the results at the two elevations may be compared.

On the basis of the simple theory which neglects magnetic effects and scattering, and assumes an isotropic distribution of the radiation at the top of the atmosphere, the intensity, $j_i(\theta)$, of a component of the radiation (defined as the number of rays per unit solid angle per cm^2 per sec.) of which the absorption coefficient is μ_i, is a function of the directions of its path through the atmosphere. At a depth h from the top of the atmosphere the intensity at angle θ from the vertical should be given by

$$j_i(\theta) = j_{0i} e^{-\mu_i h \sec \theta}. \tag{1}$$

The total intensity at angle θ is therefore given by the sum of a series of such terms corresponding to the various components of the primary radiation.

$$j(\theta) = \Sigma j_i(\theta). \tag{2}$$

Since secondary rays are also included in the measurements, this theory cannot be rigorously exact for undoubtedly the secondaries do not always follow the directions of the primary rays

[1] G. Bernardini, Nature **129**, 578 (1932).
[2] G. Medicus, Zeits f. Physik **74**, 350 (1932).
[3] L. Tuwim, Berlin Berichte **19**, 91, 360 (1931).
[4] D. Skobelzyn, Comptes Rendus **194**, 118 (1932).

which produce them, and some large angle scattering of the primary rays may also take place. Therefore, the measured distribution must be less concentrated about the vertical than that represented by (2). For this reason it would be futile to deduce values of j_{oi} and μ_i from the present data, although this would be possible on the basis of the above simple assumptions.

The apparatus consisted of three Geiger-Mueller counters mounted in line (Fig. 1) and

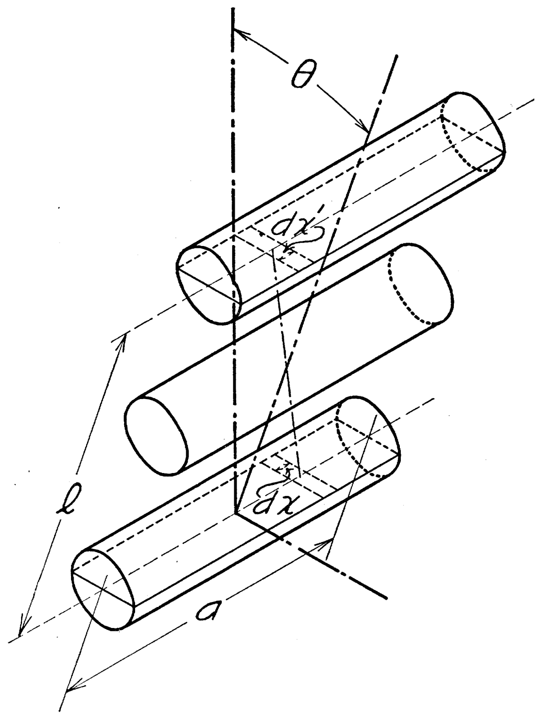

FIG. 1. Arrangement of counters.

connected for recording triple coincidences.[5] The counters were cylindrical, 12.7 cm long and 3.8 cm in diameter and were spaced 10 cm between adjacent axes. The cross-sectional area of the sensitive volume was determined by comparing the coincidence counting rate of these counters with that of a pair of counters specially constructed to eliminate end corrections. The resulting sensitive areas, assumed rectangular, were 8.8 cm by 3.8 cm. This method for making end corrections is not entirely satisfactory as it does not take account of the relative efficiencies of the two sets of counters. For the purpose at hand, however, it is sufficiently accurate, since the length of the sensitive volume enters the computations only through a small correction term.

Observations were made with the line of the counters pointing towards the magnetic south at various inclinations from the vertical. Readings were taken and the inclination changed at the end of approximately three hour intervals. A summary of the results is contained in Table I,

TABLE I. *Summary of observations.*

θ	n	T	C	r	R	R'	f	j
Mt. Washington, elevation 6280′, mean barometer 590.5 mm								
0°	6	1100	2789	2.54	0.046	0.033	0.00650	0.0165
20°	9	1487	3256	2.19	.024	.026	.00648	.0142
30°	5	909	1662	1.83	.031	.030	.00644	.0118
40°	7	1185	1635	1.38	.024	.028	.00642	.0089
60°	6	987	532	0.54	.013	.016	.00636	.0034
80°	5	1106	120	0.11	.002	.006	.00632	.00069
90°	3	664	28	0.04	.003	.005	.00632	.00025
Base station, elevation 620′, mean barometer 748 mm								
0°	8	1637	2940	1.80	0.015	0.022		0.0117
20°	5	1058	1570	1.49	.019	.025		.00966
30°	5	1198	1381	1.15	.016	.021		.00741
40°	5	1032	892	0.86	.008	.019		.00552
60°	4	729	251	0.35	.013	.015		.0022
80°	4	707	33	0.05	.005	.005		.00032
90°	1	181	8	0.04		.01		.00025

which gives, for each inclination, the number of runs n, the total time in minutes T, the total number of counts C, and the number of counts per minute r. The probable error of r as estimated from the residuals is given in the table under R.

$$R=0.6745[\Sigma v^2/(n-1)n]^{\frac{1}{2}}.$$

If no instrumental variations are present and the cosmic rays are of constant intensity, the variations should be just those arising from the statistical fluctuations. The probable error should, therefore, depend only on the number of counts C, and its value should be $R'=0.6745 \times C^{\frac{1}{2}}/T$. The values of R' are also included in the table and the agreement of R and R' is an indication of the reliability of the result. This agreement is good in every case with the possible exception of the Mt. Washington 0° value and, even there, the discrepancy is not great enough to definitely indicate trouble. For cases in which

[5] T. H. Johnson and J. C. Street, J. Franklin Inst., March, 1933.

R is less than R' the latter is the more accurate value.

Since the solid angle subtended by the counters was small, the counting rates, $r(\theta)$, are, to a fairly close approximation, proportional to the intensity $j(\theta)$, θ referring to the inclination of the line of centers of the counters. (Fig. 1.) There is, however, a small geometrical correction having a maximum variation with θ of 3 percent, which can be determined by an integration extending over the areas of the two extreme counters. Over the small range of inclinations of lines joining points on the axes of the two extreme counters, it has been assumed, for the purpose of the integration, that the intensity varies as the square of the cosine of the inclination from the vertical, this law being approximately correct empirically. Furthermore, if it be assumed that the variation of j is linear over the short range of angle subtended by the diameters of the extreme counters, integration along this dimension becomes unnecessary and the total number of rays per second passing through all three counters when pointing in the vertical direction ($\theta=0$) is given by

$$r(0)=j(0)d^2l^4\int_{-a'/2}^{+a'/2}\int_{-a/2}^{+a/2} dx'dx/[(x-x')^2+l^2]^3$$
$$=j(0)/F(0).$$

Here d is the diameter, a' and a are the lengths of the two extreme counters, and l is the distance between the extreme axes. Since the inclinations of lines joining axial points of the two extreme counters vary less and less with increasing inclination of the line joining the centers, the factor in the integral which takes account of the change of intensity of the radiation over the range of angles subtended by lengths of the counters becomes equal to unity for θ equal to $\pi/2$ and

$$r(\pi/2)=j(\pi/2)d^2l^2\int_{-a'/2}^{+a'/2}\int_{-a/2}^{+a/2}\frac{dx'dx}{[(x-x')^2+l^2]^2}$$
$$=j(\pi/2)/F(\pi/2).$$

For intermediate angles it is easy to show that

$$j(\theta)=r(\theta)F(\pi/2)(1+\epsilon\cos^2\theta)=r(\theta)f(\theta),$$

where $\epsilon=F(0)/F(\pi/2)-1$. The factors $f(\theta)$ are given in the tables as also are the corresponding values of $j(\theta)$. These values of $j(\theta)$ are still not strictly equal to the intensities, for the efficiency of the counters has not been measured and the end corrections are not accurately known. They are, however, proportional to the intensities at a single elevation. Before comparing the results at the two elevations it is necessary to investigate possible changes in the efficiency with the counting rate of the individual counters, since this changed from 100 per min. at the base station to 200 per min. on Mt. Washington.

For the purpose of this investigation the triple coincidence counting rate has been measured in the laboratory with the individual counting rates controlled by the proximity of a tube of radium emanation. These measurements consisted of a series of 34 determinations of the triple counting rates with the individual counting rates alternated between 85 per min. and 197 per min. The measurements satisfied the $R=R'$ criterion and they showed the change in coincidence counting rate to be less than the probable error (2.5 percent). Therefore, no further correction to the j values listed in the table need be applied to make them comparable at the two elevations.

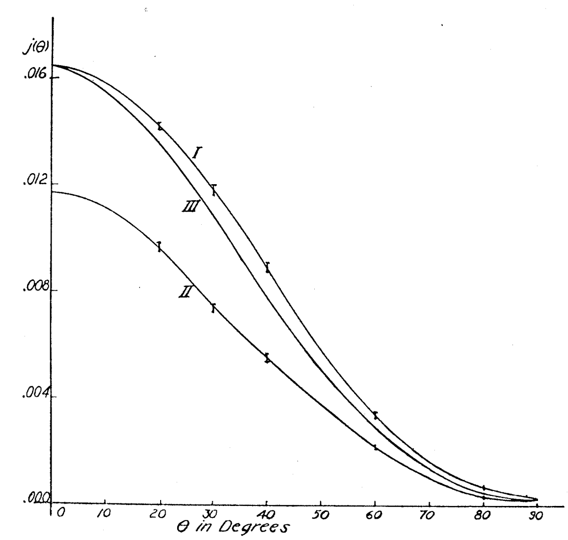

FIG. 2. Intensity of cosmic rays as function of inclination to the vertical. I. Elevation 6280 ft. II. Elevation 620 ft. III. II×1.41.

In Fig. 2, $j(\theta)$ has been plotted against θ. Curve I represents the Mt. Washington values, curve II the values at the base station and curve III has been computed by multiplying II by a constant factor. A comparison of I and III shows that the distribution is broader at the higher elevations. This is contrary to the change one would have expected on the basis of the intensities and absorption coefficients deduced by Millikan and Cameron[6] as they would have lead, on the assumptions of the simple theory, to a considerably sharper distribution at the higher elevation. The distribution at the lower elevation, however, is in good agreement with their intensities and absorption coefficients and the discrepancy at the higher elevation arises from the very intense soft component which they have deduced.

Another point of apparent inconsistency between the ionization-intensity measurements and the ray-intensity measurements is the difference in their respective variations with elevation.

The ray-intensity, J, defined as the total number of rays per cm² per second from all directions, is given by

$$J=2\pi\int_0^{\pi/2} j(\theta)\sin\theta\cos\theta d\theta.$$

The integration has been performed graphically with the results

$$J_{6280}=0.024 \text{ rays per cm}^2 \text{ per sec.}$$

$$J_{620}=0.016 \quad \text{"} \quad \text{"} \quad \text{"} \quad \text{"} \quad \text{"}$$

$$J_{6280}:J_{620}=1.46.$$

The ionization-intensities I, defined as the number of ions per cc per sec. produced by the cosmic radiation in an unshielded electroscope were computed for the barometric pressures experienced on Mt. Washington and at the base station by interpolation from the values given by Millikan and Cameron.[6] The values are:

$$I_{6280}=70.0 \text{ ions per cc per sec.}$$

$$I_{620}=36.7 \quad \text{"} \quad \text{"} \quad \text{"} \quad \text{"} \quad \text{"}$$

$$I_{6280}:I_{620}=1.91.$$

It appears, therefore, that the average ray at 6280 ft. has (1.91÷1.46) 1.31 times the ionizing efficiency of the average ray at 620 ft. elevation.

As a possible interpretation of the latter discrepancy between the ionization-intensity and ray-intensity measurements, it is suggested that the softer radiation which predominates at the higher elevations may have the greater tendency to produce groups of secondary rays in the walls of the ionization vessel. If this interpretation is correct the experiments, such as that of Schindler,[7] would be expected to show greater "übergangseffekte" at higher elevations and it would imply that the cosmic-ray ionization as measured in a closed vessel would depend upon the wall thickness and the nuclear constitution of the wall material in a way which varies with the elevation. The unexpected broader distribution at the higher elevation may have its explanation in a more predominant large angle scattering on the part of the soft rays.

The calculations are, of course, based upon the assumption of a uniform azimuthal distribution and the results would be affected by any departures from uniformity such as are indicated by the measurements on Mt. Washington made by the writer in collaboration with J. C. Street.[8]

It is a pleasure to acknowledge the cooperation of J. C. Street in developing and building the apparatus and in taking some of the readings. The writer is also indebted to H. N. Teague and Myron E. Witham of the Mt. Washington Club for the use of Camden Cottage in which the measurements on Mt. Washington were made.

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

[7] H. Schindler, Zeits. f. Physik **72**, 625 (1931).

[8] T. H. Johnson and J. C. Street, Minutes of the Atlantic City Meeting of the Am. Phys. Soc. December, 1932.