Intensity Variation of Vertical Cosmic-Ray Air Showers*

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A new experimental approach has been studied for measuring the sidereal time variation of the high-energy cosmic radiation. The apparatus consists of an "air-shower telescope" using only six small counter tubes and an "extensive" tray of GM tubes. The apparatus is sensitive to vertical showers and discriminates against showers with (projected) zenith angle greater than 10°; this directional efficiency is calculated to be about 90% and has been verified experimentally. In subsidiary experiments, the apparatus has been used to measure the zenith angle dependence of air showers. We can therefore set up an arrangement of counters to detect only vertical showers of high energy. Preliminary results show a counting rate of 1 per 3 hours per recording station for vertical extensive air showers of energy $\geq 10^{15}$ ev. The barometric coefficient has been determined as (9 ± 4)% per cm Hg; however, no statistically significant time variation has as yet been detected. The recording rate can be increased and better statistics obtained by increasing the number of recording setups.

I. INTRODUCTION

IF an anisotropy of the high-energy cosmic radiation exists, it is to be expected that any apparatus rotating with the earth will show a sidereal time variation of cosmic-ray intensity. Although several experiments[1] have already been carried out in this direction, it seems that more experimental evidence is needed to obtain general agreement on the existence of this variation.[2] Since low-energy cosmic rays are easily affected by the weak fields in the galaxy, their sidereal time variation will be small. Thus, any experiment designed to detect a sidereal time variation of cosmic rays will be expected to depend on: (1) the energy of cosmic rays to which the experimental apparatus responds; (2) the angular definition or the directivity of the apparatus, particularly so, if sources of cosmic rays exist. (3) Finally, the geographic location of the apparatus will be important since it determines the region of sky swept out. We have now designed an "air shower telescope" with very narrow receiving angle which is simple enough to be easily set up at various latitudes and which is sensitive to only high-energy cosmic rays. In the following sections we give a description of our apparatus together with the experimental results concerning its directivity and energy range, and concerning the anisotropy and barometric coefficient of extensive air showers.

II. DIRECTIVITY

From a short discussion on Hilberry's[3] experiments Singer[4] indicated that an extensive air-shower telescope can be constructed by placing counters in a vertical row and forming coincidences with other such similar sets, separated at a distance of 2 to 4 meters. The basic idea is that fewer particles are required to set off the arrangement if they come from the vertical direction. This approach, as we shall see, is fundamentally different from that of the Massachusetts Institute of Technology group in which the direction of arrival is computed from the measured differential arrival times,[5] or from the method of the Imperial College of London group in which the angle of incidence is measured from cloud chamber tracks. Relative to the latter approaches, we lose in solid angle and therefore counting rate. But this loss is not too bad since the atmosphere exercises a strong collimating effect anyway. We gain, however, due to the simplicity of our apparatus, which allows us to make many identical units.

The experimental arrangement of our telescope is shown in Fig. 1.

We require a sixfold coincidence C_6 between all three sets of two tubes each. First, we calculate the percentage of C_6 that are activated by showers coming within the aperture defined by the physical dimension and separation of the GM tubes. We know that for showers coming in within the projected zenith angle (onto a plane perpendicular to the counter tube axis) of θ_0, only a threefold coincidence is required to trigger

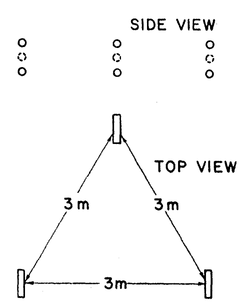

FIG. 1. Arrangement of GM tubes in the air-shower telescope (the active dimensions of the counter tubes are 43.5 cm×2.54 cm and the separation between extreme tubes is 15.24 cm). The dotted tubes were inserted to measure the directional efficiency of the telescope.

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[1] For example, F. J. M. Farley and J. R. Storey, Nature **173**, 445 (1954); A. Daudin and J. Daudin, Proceedings of the Bagnères-de Bigorre Conference on Cosmic Radiation, July, 1953 (unpublished); T. E. Cranshaw and M. Galbraith, Phil. Mag. **45**, 1109 (1954).

[2] L. Davis, Phys. Rev. **96**, 743 (1954).

[3] N. Hilberry, Phys. Rev. **60**, 1 (1941).

[4] S. F. Singer, thesis, Princeton, 1948 (unpublished).

[5] G. W. Clark, Bull. Am. Phys. Soc. Ser. II, **1**, 230 (1956).

all six tubes; hence

$$C_6(\theta \leq \theta_0) = \int_0^\infty \int_0^{\varphi_0} \int_0^{\theta_m} K\rho^{-2.4}(1-e^{-\rho a})^3 \times \cos^n\theta d\theta d\varphi d\rho. \quad (1)$$

Here $K\rho^{-2.4}d\rho$ is the previously determined[6] frequency distribution of particle density, θ is the zenith angle, φ is the azimuth angle, ρ is the local density of shower, and a is the area of a single GM tube.

$$\theta_m = \tan^{-1}[(\tan\theta_0)(\cos\varphi)^{-1}]$$

is the maximum zenith angle sustained by the telescope. The zenith angle distribution of showers is taken as $\cos^n\theta$, where n is equal to 4 in accordance with recent experiments.[7]

However, for showers coming in at zenith angles outside of the aperture defined by the telescope, a sixfold coincidence is required. The coincidence rate is given by

$$C_6(\theta \geq \theta_0) = \int_0^\infty \int_0^{\varphi_0} \int_0^{\theta_m} K\rho^{-2.4}(1-e^{-\rho a})^6 \times \cos^n\theta d\theta d\varphi d\rho. \quad (2)$$

The values of $\partial C_6/\partial\theta_0$ of (1) and (2) are plotted against θ_0 in Fig. 2. It is seen that showers within the aperture of our telescope ($\theta_0 \leq 10°$) contribute almost all of the coincidence rate C_6.

As an experimental check, we added one tube to our telescope (the dotted circles in Fig. 1) and compared the coincidence rate C_9 with C_6. The coincidence rates measured are as follows:

$$C_9 = 0.40/\text{hr} \ (\pm 0.0516),$$
$$C_6 = 0.44/\text{hr} \ (\pm 0.0580).$$

This small difference between C_6 and C_9 can be interpreted as a confirmation to our calculation that showers within the aperture of the telescope contribute almost all the coincidence rate. It is seen that a six-tube telescope is quite efficient to give us directivity as defined by the size and separation of the counting tubes.

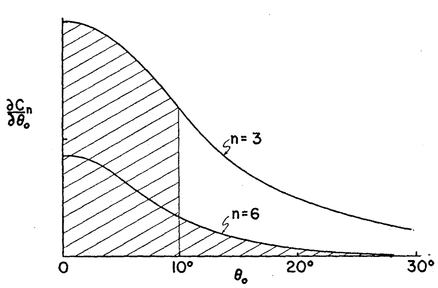

FIG. 2. Differential response of air shower telescope (at sea level) *vs* θ_0, the projected zenith angle of the incident showers. Nearly vertical showers need to cover only three counters, while showers at larger zenith angles must cover six counters in order to set off the telescope. Note the small contribution of large-zenith-angle showers.

III. ZENITH ANGLE DEPENDENCE OF SHOWERS

The same experimental setup can also be used to measure the zenith angle of extensive air showers by varying the vertical separation between counters in each individual telescope. After verifying the directional efficiency of the apparatus (see above), we varied the separation between the top and bottom of GM tubes in our sixfold telescope arrangement. The results of the experiment are given in Table I. It is seen that the experimentally measured ratio is in good accord with the calculated ratio using the $\cos^4\theta$ zenith angle dependence for $\theta \leq 10°$ found by Bassi, Clark, and Rossi.[7]

IV. ENERGY RESPONSE OF EQUIPMENT

In order to discriminate against low-energy air showers, we set up a large tray of counters of area A at a distance L from the "telescope" section as described in Sec. II. We wish now to calculate L, so that most of the showers recorded as coincidences between our "telescope section" and the large tray must have minimum energy of about 10^{15} ev.

Let the symbols ρ and a have their usual meaning as in Sec. II. If the distance between telescope sections is very small compared with the lateral spread of the shower, the sixfold coincidence rates C_6 of the telescope section [as in (1)] is proportional to

$$\int_0^\infty \rho^{-2.4}(1-e^{-\rho a})^3 d\rho.$$

The integrand is plotted against ρa in Fig. 3. It is seen that the contribution to the above integral comes mostly from the range $\rho a \geq 0.5$. Thus, C_3 records mostly showers with $\rho \geq 1/(2a)$ particles/m². The local density to which the tray of area A is sensitive is estimated as $\geq 1/(2A)$.

We now estimate the minimum energy of the shower which produces a coincidence between the telescope section and the tray A. The well-known lateral distribution function for extensive air shower is[8]

$$\phi(r) = \alpha^s[2\pi(s-1)!]^{-1}e^{-\alpha r}r^{s-2},$$

TABLE I. Experimental determination of zenith angle distribution.

	Separation between extreme counters, cm	Effective zenith angle θ_0	6-fold coinc. rate/hr
(i)	46.2	6.3°	0.3 ±0.02
(ii)	14.8	19.5°	0.46±0.025
Experimental ratio of coincidence rates (i) and (ii)			0.65±0.056
Calculated ratio assuming zenith angle distribution $\cos^4\theta$			0.62

[6] S. F. Singer, Phys. Rev. **81**, 579 (1951).
[7] Bassi, Clark, and Rossi, Phys. Rev. **92**, 441 (1953).
[8] J. Nishimura and K. Kamata, Progr. Theoret. Phys. (Japan) **6**, 628 (1951).

where r is measured in lateral units $r_0=E_s\chi_0/\epsilon$ radially outward from the direction of the primary initiating particle, and[9] $E_s=21$ Mev, $\chi_0=310m$, $\epsilon=84.2$ Mev, $s=1.4$ (at sea level).[10] With the above values, $r_0=77$ m.

Let Π be the total number of electrons in a shower at the altitude of our apparatus; then $\Pi\phi(r_1)$, $\Pi\phi(r_2)$ are the densities of electrons at distance r_1 and r_2 respectively from the core of the shower. We now set $\Pi\phi(r_1)=1/(2a)$, $\Pi\phi(r_2)=1/(2A)$, and $\Pi=10^5$ for a primary energy of 10^{15} ev.[11] In our experiment we have $a=110$ cm^2 and $A=440$ cm^2. With these values, we obtain $r_1=0.1r_0$, $r_2=0.3r_0$. In order to determine L, we let $L=\frac{1}{2}(r_1+r_2)=0.2r_0$ which equals 15.5 meters at sea level. Thus, we obtain a set of appropriate values of L, A, and a to record near-vertical showers with primary energy $\geq 10^{15}$ ev.

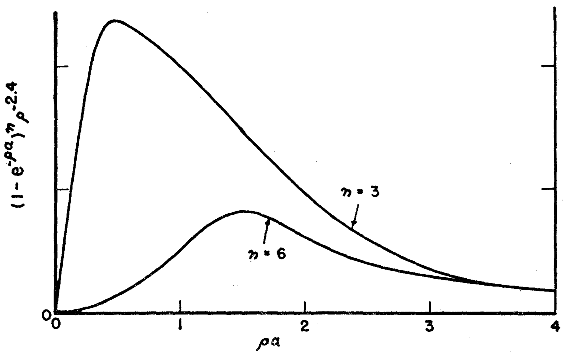

FIG. 3. Differential response of coincidence arrangement to air shower with density distribution $K\rho^{-2.4}d\rho$. The area under the curves gives the threefold or sixfold coincidence rate.

V. ANISOTROPY OF PRIMARIES

One recording station consisting of six identical telescopes of the type in Fig. 1 together with an extensive tray as discussed in Sec. IV, has been set up to measure the anisotropy of high-energy primaries. The six telescopes are located on a circle with the extensive tray at its center and radius 15.5 m. We obtain a coincidence rate of about 1 per 3 hours between each telescope and the center tray, or 2 coincidences per hour for the whole arrangement. Few coincidences between telescopes have been found so far. Based on a total operating time of six months, we have not been able to detect any significant sidereal time variation.

VI. BAROMETRIC COEFFICIENT FOR VERTICAL SHOWERS

Preliminary results of the recording stations were correlated with barometric pressure. The barometric pressures were divided into three intervals: from 29-in. Hg to 29.5-in. Hg, from 29.5-in. Hg to 30-in. Hg, and from 30-in. Hg to 30.5-in. Hg. We obtain a value of 0.09 ± 0.041 cm^{-1} Hg for the barometric coefficient, in good agreement with other experiments.[12]

It would, however, be of considerable interest to carry the equipment to airplane altitudes in order to obtain the altitude dependence (and position of the maximum) for vertical showers.

VII. CONCLUSIONS

We have been able to demonstrate experimentally that a simple multiple-telescope arrangement has high directivity for extensive air showers. The arrangement is therefore suitable for measuring the zenith angle dependence of extensive air showers, for measuring barometric coefficient of air showers, for example in the vertical direction, and for similar refined experiments. The arrangement is also suitable for studying the anisotropy of high-energy primaries by measuring the sidereal diurnal variation of extensive air showers. The directivity allows a high degree of resolution. In this respect the equipment is similar to a radio-telescope which measures the distribution of radio noise in the galaxy. We "tune" the apparatus to high-energy cosmic rays essentially by decreasing areas and requiring high particle densities for detection in the apparatus. It would be possible to increase the directivity further but at the expense of solid angle and therefore counting rate. The present resolution of 10° may represent an optimum compromise since scattering of shower particles takes place in the atmosphere which is estimated to be of the order to 5° and since the primaries themselves may be deviated a few degrees by extraterrestrial magnetic fields.

We have as yet no evidence for a sidereal time variation; however, we plan to increase the counting rate and therefore statistics by multiplying the number of equipments; this is similar to increasing the aperture of a radio telescope.

[9] B. Rossi, *High-Energy Particles* (Prentice Hall, Inc., New York, 1952).
[10] Barrett, Bollinger, Cocconi, Eisenberg, and Greisen, Revs. Modern Phys. **24**, 133 (1952).
[11] M. Oda (unpublished).
[12] K. Greisen, in *Progress in Cosmic-Ray Physics*, edited by J. G. Wilson (Interscience Publishers, New York, 1956), Vol. III, p. 73.