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Isotropy of cosmic rays with energies 5 TeV to 100 TeV

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A cosmic-ray isotropy measurement was carried out using about 10^6 underground muon events. The directional properties of the detector allowed events to be separated into bins according to the depth of rock penetrated and the celestial angles of the primary particles. The result at a median primary energy of 12 TeV, for muons penetrating an average depth of 2.9×10^5 g cm^{-2}, was a diurnal anisotropy of $(0.1 \pm 0.2)\%$. No single $10° \times 10°$ angular bin showed a significant excess of particles. The deviation from the expected numbers per bin showed a normal distribution with standard deviation no larger than that expected from counting statistics. This allowed a limit to be set on the angular roughness of the cosmic-ray flux.

I. INTRODUCTION

Cosmic-ray anisotropy measurements, at energies above 10^{11} eV, should help answer the following astrophysical questions: (1) Where are the sources of cosmic rays? (2) What type of magnetic field exists between the sources and the earth? Although these questions are not resolved by the data in this paper, constraints are established for future reference.

The present experiment is able to set some new limits to the diurnal and semidiurnal sidereal anisotropies, although it was principally designed to search for narrow-angle cosmic ray anisotropies, as suggested by the adiabatic propagation model.[1] Narrow-angle anisotropies have been reported[2-5] only at energies between 100 and 400 GeV. The apparatus and procedures of the present experiment are discussed in Sec. II. The results are given in Sec. III and discussed in Sec. IV.

II. PRESENT EXPERIMENT

A. Apparatus and data collection

The University of Utah muon detector has a geometrical factor of approximately 80 m^2 sr and is located about 560 m below the surface in mountainous terrain near Park City, Utah. The apparatus, which has been described elsewhere,[6] records information on magnetic tape which is later decoded by computer to yield the angles of arrival for each muon event. These angles and other data, including the time of the event, are written onto another magnetic tape for further analysis by the binning program.

The direction of origin of an event in celestial coordinates is computed in the binning program. The depth of rock penetrated by the muons is also known as a function of the angles. In this way the binning program can bin the data by celestial angles ($10° \times 10°$ bins), and also by depth and muon multiplicity. The angular precision, in both azimuth and zenith angles, is about 1°. This is the observed angular spread between muons in multiple-muon events.[6]

Owing to triggering inefficiency a fraction (less than 20%) of the single-muon events were not detected. The triggering efficiency was continuously monitored, along with other indicators of equipment difficulties. A small percentage of the events were ambiguous to the computer pattern-recognition program and were automatically rejected. The data runs lasted a few days each, some integral number of sidereal days plus a fraction of a sidereal day left over. The fractional days were discarded, along with any runs having equipment malfunctions during the run. The data used should thus have constant efficiency versus sidereal time.

No atmospheric corrections to the data were made or found to be necessary. At these energies less than 0.2% of the muons decay in the atmosphere, so that small changes in the production height (as indicated by barometric pressure) would have negligible effect. The event rates, for most of the data, were studied for solar and sidereal waves, both diurnal and semidiurnal. As a further consistency check on these data, the event rates were studied as a function of the time since the apparatus was turned on at the beginning of each run.

B. Primary Energies

The events were separated into ten categories or bins of muon multiplicity and slant depth h of rock penetration by the muons. Table I shows the muon energies and the median energies of primary protons or alpha particles contributing to each category as calculated in a Monte Carlo program.[7] This program used accelerator data on the production of protons, pions, and kaons, along with the assumption of scaling to predict results at the high energies considered. Also shown is the

TABLE I. Primary energy vs muon multiplicity and depth h.

Mult.	h (10^2 g cm^{-2})	E_μ (TeV)	E_p (TeV)	E_α (TeV)	No. of events
1	1900	1.1	7	28	203 355
1	2900	1.8	12	48	466 320
1	3900	2.8	19	76	101 494
1	4900	4.1	29	120	25 777
1	5900	5.8	41	160	7013
1	>6400	>6.9	>50	>200	2237
2	1900	1.1	44	110	32 741
2	2900	1.8	73	190	23 008
2	>3400	>2.2	>95	>240	4074
3	>1400	>0.8	>150	>300	21 044

mean muon energy for the middle depth and the number of events in each bin.

The median primary energies E_p and E_α in Table I have been calculated for the listed middle depth of a depth bin, rather than for the properly weighted average depth, which would take into account the distribution of depths and muon rates within a depth bin. Thus, they are only approximate indications for the median energy of the events within a bin. There is a wide range of primary energies contributing to each bin, such that about two thirds of the events are within a factor of three above or below the energy quoted. This causes an overlapping of energies in adjacent depth bins. If an anisotropy were present in one depth bin it would also necessarily be present to a certain extent in all bins of less depth. Such correlations would provide a consistency check and some indication of the energy of any anisotropy found.

III. EXPERIMENTAL RESULTS

A. Event rates

The data were divided into four sets, containing 132, 88, 90, and 78 sidereal days of usable data, respectively. The data were taken from April, 1971, to June, 1974, during which time the detection efficiency declined about 10% as shown by the average number of events per day: 2423 ± 4, 2292 ± 5, 2284 ± 5, and 2212 ± 5. This represents a decline of about 0.01% per day, which would be entirely negligible by itself. Minor equipment malfunctions occur on a short time scale, however, and may be repaired only between runs. The result might be a declining average efficiency during a typical run. To check for possible bias due to such problems, the event rate was studied as a function of time since the starting time of each run, t_{on}. There was no significant bias, as seen in Table II. Only the last three data sets were checked in this way, but the same selection criteria were also used for the first data set,[8] and the results of the first data set do not differ significantly from the others.

Analyzing the last three data sets versus local sidereal time and local solar time yielded no significant departures from uniformity (see Table II). One would expect a solar effect due to temperature, having phase similar to that in Table II but somewhat larger amplitude.[9] The last data set had the largest amplitude for each category, the largest being $(0.89 \pm 0.33)\%$ with peak at $t = 3.9$ h sidereal time. The amplitude C is given by $C = (A^2 + B^2)^{1/2}$, where A and B are the Fourier expansion coefficients. A and B have Gaussian distributions with the given standard deviation σ. The probability of an amplitude greater than C, due to counting statistics only, is

$$P(>C) = \exp(-C^2/2\sigma^2) .$$

The amplitude of rates versus sidereal time in Table II contributes only indirectly to the sidereal anisotropy in the present experiment, since most of the muon events occur with zenith angles of 40 to 60 degrees from the vertical.

TABLE II. Event rates vs time.

Time parameter	Diurnal $C \pm \sigma$ (%)	Max (h)	Semidiurnal $C \pm \sigma$ (%)	Max (h)
$t - t_{on}$ (sidereal h)	0.24 ± 0.18	23.5	0.17 ± 0.17	11.5, 23.5
t (sidereal h)	0.43 ± 0.18	2.0	0.31 ± 0.17	8.4, 20.4
t (solar h)	0.15 ± 0.19	15.3	0.25 ± 0.19	7.8, 19.8

TABLE III. Fourier amplitude and right ascension of peaks.

E_p (TeV)	Diurnal $C \pm \sigma$ (%)	Max (deg)	Semidiurnal $C \pm \sigma$ (%)	Max (deg)
7	0.4 ± 0.3	29	0.5 ± 0.3	98
12	0.1 ± 0.2	306	0.2 ± 0.2	151
19	0.1 ± 0.4	98	0.4 ± 0.4	77
29	0.9 ± 0.9	43	1.9 ± 0.9	38
41	2.0 ± 1.7	39	0.2 ± 1.7	26
>50	5.0 ± 3.0	349	3.3 ± 3.0	162
44	1.2 ± 0.8	229	0.7 ± 0.8	1
73	1.6 ± 0.9	64	1.5 ± 0.9	104
>95	1.6 ± 2.2	161	7.6 ± 2.2	101
>150	1.1 ± 1.0	98	2.0 ± 1.0	73

B. Directional isotropy

For each depth bin the raw data were summed by declination and analyzed for diurnal (24 h) and semidiurnal (12 h) sidereal waves. The results are summarized in Table III. It can be seen that none of the sidereal waves listed are significant, with the possible exception of the semidiurnal wave in the ninth depth bin. A recent anisotropy result[10] for 60 TeV air showers, $(0.08 \pm 0.03)\%$ with maximum at 4.5 h, would preclude any real anisotropy in the ninth depth bin, however, since the same energies are included in the air-shower result.

To claim a significant anisotropy at the 1% level of confidence, one of the twenty amplitudes should exceed 3.9σ. None did.

The results for the lowest energy in Table III are compatible with a previous anisotropy measurement[9] at slightly less depth (1.57×10^5 g cm^{-2}), which yielded $(0.1 \pm 0.3)\%$. Our best measurement is at a median primary energy of 12 TeV, yielding $(0.1 \pm 0.2)\%$.

Because of the location of the detector under mountainous terrain, the instrument had a sensitivity which depended both on the declination and depth of the bin considered. This sensitivity is indicated in Table IV by the standard deviation for the number of particles per bin.

Because of the large number of $10^\circ \times 10^\circ$ bins considered, at various depths, an individual bin would need an excess of more than 4.5 standard deviations to be significant by itself at the 1% level. No significant single bins were found. Grouping nine bins into $30^\circ \times 30^\circ$ bins also failed to locate any significant narrow-angle anisotropy. Among single bins or combinations of nine bins none had positive deviations larger than 3.3 times the appropriate standard deviation. The distribution of scores for individual bins fitted well to a normal distribution, as tested with χ^2.

A limit for the angular roughness or texture of the cosmic-ray distribution can be obtained by comparing the scatter in the data to that expected from counting statistics. The standard deviations in Table IV are given by $\sigma = (35/36\,\bar{N})^{1/2}$, since the number in a bin is compared to $\bar{N}$, the average N for 36 bins in that declination. For each bin with $\bar{N} > 10$ the standard score s was computed, $s = (N - \bar{N})/\sigma\bar{N}$. The rms value of s for 3024 bins was 0.967, slightly less than the expected 1.000 ± 0.013. At the 1% confidence level, the rms value of s can be said to be less than 1.030. This would correspond to an independent source of deviation less than 0.25σ for the typical bin. This limit on roughness is in addition to the limits already set for a significant single bin or a sidereal wave.

IV. DISCUSSION

The results are compatible with previous measurements and give some new limits on the diurnal and semidiurnal anisotropy at several energies in a range below that accessible to small

TABLE IV. Standard deviations (%) for $10^\circ \times 10^\circ$ bins.

E_p	Average declination (deg)										
(TeV)	75	65	55	45	35	25	15	5	−5	−15	−25
7	7.1	5.0	3.7	3.5	3.3	2.5	3.1	12.2	···	···	···
12	5.0	5.1	4.2	3.4	2.7	2.3	1.9	1.9	2.3	6.1	···
19	12.9	6.6	5.8	5.3	4.8	4.6	5.1	5.8	7.7	7.5	22.7
29	···	16.4	13.2	16.5	15.0	10.0	12.0	11.5	10.0	8.6	11.3
41	···	56.4	24.7	30.6	24.2	27.1	21.5	16.0	16.7	24.2	24.1
>50	···	74.0	46.9	54.0	52.1	36.3	31.5	33.0	35.1	47.1	39.1
44	14.3	10.4	8.7	8.2	7.6	7.1	9.3	28.7	···	···	···
73	21.7	22.2	19.1	13.9	11.7	11.4	9.1	8.1	10.2	25.2	···
>95	61.7	31.6	29.7	27.2	25.1	24.0	29.5	31.4	35.4	30.0	47.1
>150	19.3	14.5	12.3	11.0	10.0	9.9	11.0	13.8	18.6	41.4	···

air showers. Limits are set for any narrow-angle anisotropy confined to either a $10^\circ\times10^\circ$ bin or a $30^\circ\times30^\circ$ bin. A limit is also set for the over-all texture or roughness of the particle distribution versus angle at the various depths considered.

These results are compatible with the diffusion models for cosmic-ray propagation. They are also compatible with the adiabatic propagation model, but put some constraints on the distribution of sources or the smoothness of the galactic magnetic field. The adiabatic propagation model is not very sensitive to the size or intensity of the individual cosmic-ray sources, as long as their total intensity in the galactic disk is unchanged.

In the context of the adiabatic model, two possibilities must be considered, the first being that the magnetic flux lines are not confined to the galactic disk, but traverse the halo or even regions of intergalactic space. This would remove the typical source to a large distance, reducing the size of the anisotropy produced and lengthening the cosmic-ray lifetime. (This may eventually be tested using the decay of Be^{10}.) The second possibility is that the galactic magnetic field has sufficient irregularities of appropriate sizes to obscure narrow-angle anisotropies at energies above 5 TeV, even with sources and magnetic fields confined to the galactic disk. Detailed anisotropy measurements below 5 TeV should help resolve this question in the future.

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