ISOTROPY OF UNDERGROUND MUONS*

S. C. Barrowes,[†] J. Elbert, E. Jaehne, G. Mason,[††] H.E. Bergeson

Department of Physics, University of Utah
Salt Lake City, Utah 84112

The present anisotropy search, reflecting the arrival directions of about 375,000 primary cosmic rays of energy greater than 5 TeV, was motivated by a theory which predicts the number of narrow-angle anisotropies to be expected on the basis of the galactic magnetic field being smooth on the small scale. The binning of underground muon events by different slant depths and muon multiplicities provided da.ta at a number of energy ranges from 5 TeV to greater than 150 TeV, The degree of isotropy observed requires a significant amount of scattering at these energies over the cosmic ray lifetime. No significant anisotropies were observed.

1. Introduction.

This anisotropy search was motivated by a theory for cosmic ray anisotropies (Barrowes 1972), based on the assumption that the magnetic field of the galaxy is smooth on the small scale. This assumption was supported by the fact that small-scale irregularities decay more quickly (lifetime inversely proportional to linear dimension squared) and that the energy requirements to maintain them would therefore be excessive (Kulsrud and Cesarsky 1970; Jokipii 1971).

Cosmic ray particles would then spiral along the magnetic field lines to great distances from the source, maintaining their pitch angles and giving rise to bright patches or anisotropies in the cosmic ray flux observed at the earth.

The particular anisotropies visible would depend on what source(s) had crossed near our particular field lines in the magnetic field of the galaxy and thereby left a "curtain" of cosmic rays spiraling along these field lines toward us.

The theory would be more applicable at lower energies (because small-scale magnetic irregularities decay faster) than in the present experiment where E 5 TeV. The probable number of anisotropies is also much greater in the

---

* Research supported by the National Science Foundation.

[†] Dept. of Physics and Astronomy, Louisiana State University, Raton Rouge, Louisiana., 70803.

[††] Dept. of Physics, Brigham Young University, Provo, Utah

interval 0.1 to 0.5 TeV, where narrow-angle anisotropies with compelling statistics have a apparently been observed (Sekido, Yoshida, and Kamiya. 1959, and in one case confirmed by a separate experiment (Buka.ta. and Standil 1965; Wang and Lee 1969). The rarity of higher energy anisotropies is due to the smaller number of sources needed in view of the steeply falling cosmic ray spectrum and the greater power of the individual high energy sources (accordin- to the pulsar model of Ostriker and Gunn (1969), and Ostriker (1970)).

To estimate the probability of an anistropy at 10 TeV energy from the table in Barrowes (1972), we notice that the number arising from sources crossing our flux line in the last 3 x 10^5 years would be about 0.07. A Pulsar source within 3 x 10^5 l. y. should provide a flux equal to 1.4 times the observed integral background flux with that average energy. The diameter of the galaxy is about 10^5 1. y., so that considering larger distances would probably include multiple paths around whatever magnetic field loops exist in the galaxy. Because the drift velocity of a source would be only about 10^{-4} C, these multiple paths would cover only a small part of the volume of the galaxy by the time 3 x 10^6 years into the past was considered. Entropolating the table this far would give about 7 sources, each having on the average 1/7 of the total flux. At higher energy fewer sources, each with a. greater share of the total flux would be implied.

It is clear that if approximate isotropy is observed at the higher energies that the above picture is not adequate, since it implies very large observable irregularities. Thus it would be implied that some scattering of cosmic rays must be included in the case of high energies and great distances.

In the present experiment, any anisotropy which could be established would be helpful in determining how much scattering should be considered, and at what energy it becomes important. At enemies above 5 TeV, perturbations in the magnetic field in and around the solar-wind cavity would have little effect, and any anisotropy should be essentially unchanged on a time scale of centuries.

2. Procedures. The experimental data was obtained using the Utah neutrino detector, located about 560 m underground in an old mine near Park City, Utah. This detector, which has been described elsewhere (Davis et a1 1971) 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^{1} x 10^{1} bins), and also by depth and muon multiplicity. The angular lag precision, in both azimuth and zenith angles, is about 1^{1} . This is the observed angular spread between muons in multiple-muon events (Davis *et al* 1971).

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. The data used would then be of approximately constant efficiency versus sidereal time. No atmospheric corrections were made, for simplicity and because narrow-angle anisotropies were being sought.

The median energies of primary protons or alphas contributing to each depth and multiplicity have been calculated using a Monte Carlo program developed by two of the authors (G.M. and J.E.). This program uses accelerator data on the production of protons, pions, and kaons, along with the assumption of scaling to predict results at the high energies considered.

These madian primary energies have been calculated for the 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. Thins, they are only approximate indications for the median energy of the events within a bin.

3. Results. The data collected represent a running time of 157 sidereal days between April 1971 and September 1972. In Table I are listed the number of events gathered in each depth bin for the muon multiplicities shown. Also listed are the mean muon energy $E_{ì}$, for the middle depth in each bin and the corresponding median primary energy for incident protons, E_p, and alphas, $E_{á}$.

It is worth noting that because of the number of bins considered, a single bin would need more than five standard deviations to be significant by itself. No significant single bins were found. Nor did grouping the data into groups of 4, 9, 25 and 81 bins produce any significant grouping of bins by this criterion. The distribution of scores for individual bins fit well to a normal distribution, as tested with chi squared. Thus the da.ta, show no significant anisotropy and is consistent with isotropy at the present level of measurement.

This is consistent with previous results (Davis et al 1971) obtained from the same detector, using about a third as much data. taker. through most of 1970.

TABLE I

PRIMARY ENERGY vs. MUON MULTIPLICITY AND DEPTH h

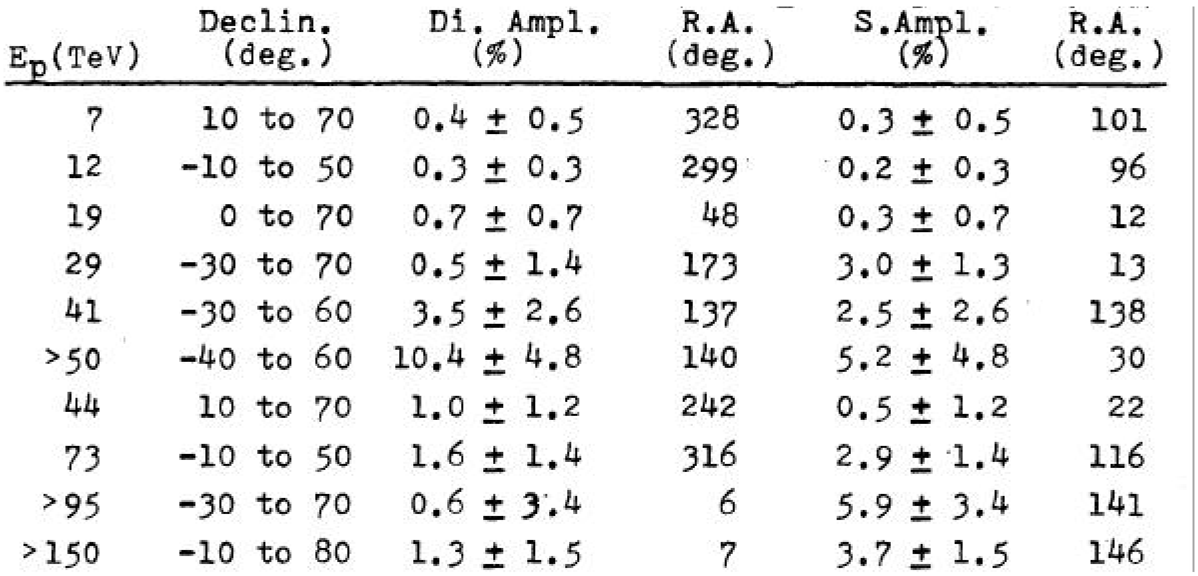
Mult,	h (hg cm^{-2})	$E_{ì}$ (TeV)	E_p(TeV)	$E_{á}$(TeV)	No.Event.
1	1900	1.1	7	28	86,810
1	2900	1.8	12	48	195,970
1	3900	2.8	19	76	43,248
1	4900	4.1	29	120	10,997
1	5900	5.8	41	160	2,962
1	>6400	>6.9	>50	>200	868
2	1900	1.1	44	110	13,753
2	2900	1.8	73	190	9,620
2	>3400	>2.2	>95	>240	1,768
>3	>1400	>0.8	>150	>300	8,970

If an anisotropy feature had shown up in the data of one depth bin, it would also necessarily be present to a. certain extent at all bins of less depth (lower energy). Such checking would provide some measurement of the primary energy of an anisotropy 'as well as additional statistical verification. Another checking procedure which is helpful in evaluating apparent "patterns" is to generate sets of random scores for comparison.

There has been a. bi-directional anisotropy reported by Jacklyn (1966) and confirmed by Sekido et a1 (1971) , at primary energies of about 100-200 GeV. This amounts to broad intensity peaks of about 0.1% above background in the two directions ä = $35^{ì}$ N, R.A. = 18 h = $270^{ì}$, and ä = $35^{ì}$, R.A. = 6h = $90^{ì}$. To test whether a. corresponding anisotropy exists at E 5 TeV, patches of sky $50^{ì}$ x $50^{ì}$ centered near these positions were compared to background. None of these patches showed positive excesses beyond 1.6 standard deviations, and almost half the deviations were negative. Since the standard deviations were 0.7% or larger, they would not show an effect as small as that reported at lower energy.

The raw data were summed by declination and analyzed for diurnal (24 hour) and semidiurnal (12 hour) sidereal waves. The results are summarized in Table II. The declinations for which the detected particle numbers are at least a fourth of the maximum value are listed. It can be seen that none of the sidereal waves listed are significant, although some of them seem to correlate with an adjacent depth bin.

TABLE II
DIURNAL AND SEMI-DIURNAL FOURIER AMPLITUDES AND R.A. OF PEAK



E_p(TeV)	Declin. (deg.)	Di. Ampl. (%)	R.A. (deg.)	S.Ampl. (%)	R.A. (deg.)
7	10 to 70	0.4 ± 0.5	328	0.3 ± 0.5	101
12	-10 to 50	0.3 ± 0.3	299	0.2 ± 0.3	96
19	0 to 70	0.7 ± 0.7	48	0.3 ± 0.7	12
29	-30 to 70	0.5 ± 1.4	173	3.0 ± 1.3	13
41	-30 to 60	3.5 ± 2.6	137	2.5 ± 2.6	138
>50	-40 to 60	10.4 ± 4.8	140	5.2 ± 4.8	30
44	10 to 70	1.0 ± 1.2	242	0.5 ± 1.2	22
73	-10 to 50	1.6 ± 1.4	316	2.9 ± 1.4	116
>95	-30 to 70	0.6 ± 3.4	6	5.9 ± 3.4	141
>150	-10 to 80	1.3 ± 1.5	7	3.7 ± 1.5	146

4. Conclusions. On the basis of the degree of isotropy we observe, there is a need to include some scattering of particles at 10 TeV and above, as they propagate through the galaxy. A propagation model which includes this as a perturbation of the otherwise adiabatic propagation needs to be worked out.

We have no significant anisotropies to report. The irregularities present appear to be consistent with random fluctuations of an isotropic cosmic ray flux at the energies considered.

Barrowes, S, C. 1972, Astrophys. J., 177, 45.
Bukata, R. P, and Standil, S. 1965, Canadian J Phys., 43, 883,
Davis, K. H., Fall, S. M., Ingebretson, R. B., and Stenerson, R. 0. 1971, Phvs. Rev. D, 4, 607.
Jacklyn, R. M. 1966, Proceedings International Conference on Cosmic Rays (London), p . 141.
Jokipii, J, R, 1971, Conference Papers (University of Tasmania), 1, P. 401.
Kulsrud, R. M., and Cesarsky, C. J. 1971, Astrophvs- Letters, 8. 189.
Ostriker, J. P. 1970, Acta Phys. Hungaricae, Z2, Suppl. 1, 352,
Ostriker, J, P,, and Gunn, J. E. 1969, Astropphys. Js, 157, 1395.
Sekido, Y,, Nagashima, K., Kondo, I., and Sakakibara, S, 1971, Conference Papers (University of Tasmania), 1, p. 302, Sekido, Y., Yoshida, S., and Kamiya, Y, 1959, Phvs. Rev., 1108.
Wang, C. P. and Lee, A. H, 1969, J. Geophys, Res., 24, 2439.

Filename: icrc771-616
Directory: C:\WINDOWS\Desktop\Amy's Papers
Template: C:\Program Files\Microsoft Office\Templates\Normal.dot
Title:
Subject:
Author:
Keywords:
Comments:
Creation Date: 07/17/01 6:05 PM
Change Number: 3
Last Saved On: 08/20/01 9:30 AM
Last Saved By: user
Total Editing Time: 554 Minutes
Last Printed On: 10/08/01 11:34 AM
As of Last Complete Printing
  Number of Pages: 5
  Number of Words: 1,576 (approx.)
  Number of Characters: 8,987 (approx.)