and S. B. Trieman, Phys. Rev. Letters 14, 518 (1965); J. M. Cornwall, P. G. O. Freund, and K. T. Mahanthappa, Phys. Rev. Letters 14, 515 (1965).

[6] In reference 1 it states that the three-meson decays involving 3π, $\eta+2\pi$, $\rho+2\pi$, and $\omega+2\pi$ are comparable. Actually, it is found that the $\rho+2\pi$ and $\omega+2\pi$ modes are favored over the 3π and $\eta+2\pi$ modes, although it probably is still insufficient to account for the vast differences in decay rates between these two types of processes without introducing symmetry-breaking effects. The $\rho+2\pi$ and $\omega+2\pi$ modes are found to be comparable. For a detailed list of branching ratios, see reference 2.

[7] H. Harari, H. J. Lipkin, and S. Meshkov, Phys. Rev. Letters 14, 845 (1965).

[8] The absence of this term implies that the magnitudes of the $\rho_+\pi_-(2\pi)$, $\rho_-\pi_+(2\pi)$, and $\rho_0\pi_0(2\pi)$ amplitudes are the same, and that the introduction of this term displaces the magnitude of the $\rho_+\pi_-(2\pi)$ amplitude one way, and that of the $\rho_-\pi_+(2\pi)$ amplitude the other way with equal amounts. Therefore, the statistical average of the $\rho+3\pi$ processes should not be greatly perturbed.

[9] See reference 1 for a summary of the experimental data.

[10] R. Armenteros et al., Phys. Letters 17, 170 (1465); N. Barash et. al., "Antiproton Annihilation in Hydrogen at Rest I, Reaction $\bar{p}+p\rightarrow K+\bar{K}+\pi$" (to be published).

EVIDENCE FOR HIGH-ENERGY COSMIC-RAY NEUTRINO INTERACTIONS*

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The flux of high-energy neutrinos from the decay of K, π, and μ mesons produced in the earth's atmosphere by the interaction of primary cosmic rays has been calculated by many authors.[1] In addition, there has been some conjecture[1] as to the much rarer primary flux of high-energy neutrinos originating outside the earth's atmosphere. We present here evidence[2] for the interactions of "natural" high-energy neutrinos obtained with a large area liquid scintillation detector (110 m^2) located at a depth of 3200 m (8800 meters of water equivalent, average $Z^2/A \simeq 5.0$) in a South African gold mine.

The essential idea of the present experiment[3] is to detect the energetic muons produced in neutrino interactions in a mass of rock by means of a large area detector array imbedded in it. Backgrounds are reduced by the large overburden and by utilizing the fact that the angular distribution of the residual muons from the earth's atmosphere is strongly peaked in the vertical direction at this depth. The angular distribution of the muons produced by neutrino interactions should show a slight peaking in the horizontal direction.[1]

The detector array, shown schematically in Fig. 1, consists of two parallel vertical walls made up of 36 detector elements. The array is grouped into 6 "bays" of 6 elements each. Each detector element, Fig. 2, is a rectangular box of Lucite of wall area 3.07 m^2 containing 380 liters of a mineral-oil based liquid scintillator,[4] and is viewed at each end by two 5-in. photomultiplier tubes. The array constitutes a hodoscope which gives a rough measurement of the zenith angle of a charged particle passing through it. In addition, the event is located along the detector axis by the ratio of the photomultiplier responses at the two ends. The sum of the responses then pro-

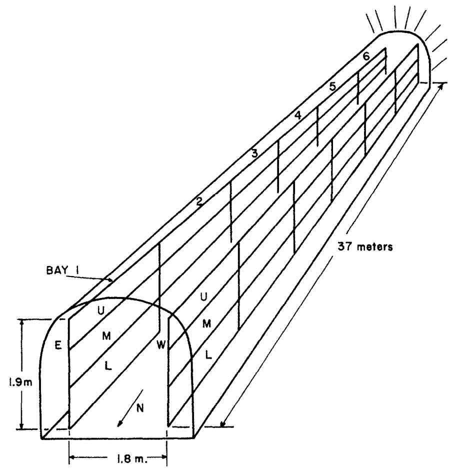

FIG. 1. Schematic of detector array.

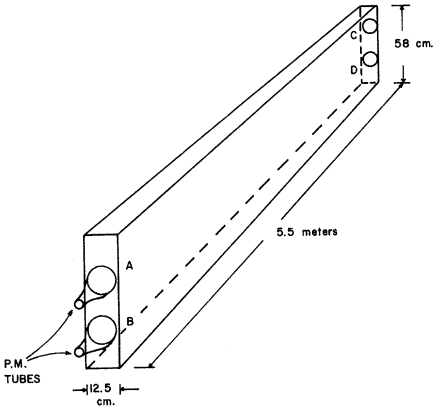

FIG. 2. Sketch of detector element.

vides a measure of the energy deposited and hence the track length in the detector. The scintillator is 20 MeV thick for minimum ionizing particles, well above energies characteristic of natural or induced radioactivity. Pulses from every photomultiplier tube were presented on two oscilloscopes, one for each side (E or W) of the array, and photographed whenever at least a fourfold coincidence of the type A_E, B_E, C_E, D_E or A_W, B_W, C_W, D_W occurred. The four tubes responsible for the coincidence, although on the same side (E or W), were not required to be located in the same detector element. A coding system consisting of signal mixers and delay lines was used to identify the photomultiplier tubes on the oscilloscope traces. A second system in which the pulse amplitudes from individual tubes were stored as charges on condensers was also employed during the phase of the experiment reported here. Calibration and system checks were accomplished by means of a light pulser placed at the center of the detector elements, an electronic pulser, and a Y^{88} source, the response to which was related to the signal from cosmic rays as seen in an identical detector element located above ground. The fourfold accidental coincidence rate is $\ll 1$/yr for energies >15 MeV. From data obtained with this system, it was possible to deduce the flux and information regarding the direction—but not sense—of the charged particles which penetrated the detector.

The system was set into operation, one bay at a time, starting in September 1964, and all six bays were completely operational by June 1965. To date we have logged 563 bay days of operation. Allowing for the solid angle seen by the detector, this corresponds to 14 200 m^2 days sr or the equivalent of all six bays for 94 days. Tables I, II, and III list events of various classes, their time of occurrence, the detector elements involved, the energy deposited, and, for events in which more than one tank gave a signal, the locations in the tanks. Figure 3 is a sample reconstruction of an eightfold event, the event of 23 February 1965.

We now present estimates of the extent to which various processes involving ordinary cosmic-ray muons can contribute to the events

Table I. Eightfold events (coincidences involving one element of each side). Run time for events was 563 bay days.

Date	Time, Greenwich (h)	Tank	Location of events (meters from north end)	Energy deposited in detector (MeV)
23 February 1965	21:48	E4*L*	2.1	29
		W4*L*	2.8	18
1 March	00:20	E5*M*	0.03	55
		W5*U*	4.9	118
17 March	18:52	E4*L*	3.6	19.4
		W4*L*	1.7	16.0
20 April	14:16	E2*M*	4.6	23.5
		W2*M*	3.4	24.5
1 June	22:37	E1*L*	5.5	18.5
		W2*L*	0.55	18.0
3 June	01:42	E4*U*	2.4	5.0
		W4*M*	3.7	18.0
1 July	15:21	E3*M*	1.3	21.0
		W3*U*	3.0	30.0

Table II. Miscellaneous multitank events. Run time for events was 563 bay days.

Date	Time, Greenwich (h)	Tank	Location of event (meters from north end)	Energy deposited in detector (MeV)
27 October 1964	19:39	E1*M*	3.6	58
		E1*L*	?	~10
		W1*U*	1.1	158
		W1*M*	2.3	116
		W1*L*	2.4	37
13 December	10:31	E2*M*	3.4	75
		E2*L*	2.1	59
22 December	11:03	E1*U*	3.7	37
		E1*M*	4.3	51
		E1*L*	4.6	16
11 February 1965	02:20	E1*U*	1.7	84
		E1*M*	1.6	78
		E1*L*	1.8	21
14 February	22:35	E4*M*	3.9	65
		E4*L*	?	?
		E5*M*	0.09	51
		W4*M*	2.9	49
		W4*L*	4.2	34
7 May	02:10	W5*M*	1.8	65
		W5*L*	1.4	97
12 June	13:40	E3*U*	3.9	60
		E3*M*	3.4	122
		E3*L*	1.7	19

listed in Table I.

(1) The angular distribution of muons at this depth can be calculated from the known depth-intensity curves.[5] Normalizing the intensity to the rate of vertical events listed in Tables II and III we find that <1 muon/yr produces a coincidence of the type listed in Table I.

(2) The energy distribution of the muons at this depth can also be determined from the depth-intensity relation. From this spectrum it is estimated the contribution to Table I events due to muons which have multiply scattered is negligible.

Table III. Single-tank events with energy deposition >18 MeV.[a] Run time for events was 265 days.

Date	Time, Greenwich (h)	Tank	Energy deposited (MeV)
9 November 1964	00:48	E1*L*	45
23 November	16:05	E1*L*	48
25 November	15:09	E1*L*	63
14 February 1965	02:52	W5*M*	26
24 February	15:04	W2*M*	39
11 March	11:03	E4*L*	54
11 March	21:40	W5*M*	51
12 March	15:38	E2*L*	26

[a] Data only reduced for period to 18 March 1965.

(3) In a similar fashion it can be shown that the number of Table I events produced by high-energy knock-on electrons or electromagnetic showers is negligible.

(4) The contribution expected from stars produced by muons is estimated from star production cross sections measured underground (at 500 meters of water equivalent)[6] to be much less than 3/yr.

(5) It is conceivable that pairs of associated high-energy muons may be responsible for events of the type listed in Table I. One argument against this interpretation is the fact that the energy deposition which would be expected from such nearly vertical particles would be much larger than observed. It is to be noted that two events of Table II (27 October and 14 February) are consistent with this multiple-muon hypothesis. This phenomenon is being studied further.

From these arguments regarding the contributions of ordinary cosmic-ray muons to the

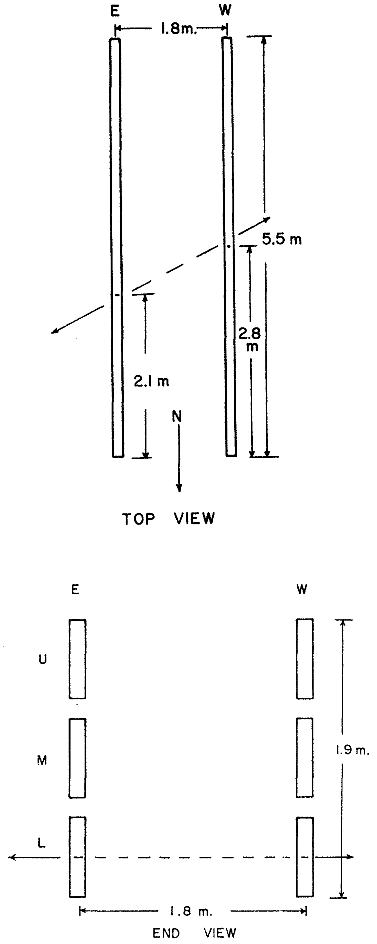

FIG. 3. Reconstruction of event of 23 February 1965.

events of Table I, it appears difficult to explain these events by known processes involving these muons. It is therefore plausible that the events of Table I are due to neutrino interactions. An estimate of the expected rate due to neutrinos produced in the earth's atmosphere is appropriate at this point.

In the following calculations we assumed a neutrino spectrum $(\nu_\mu + \bar{\nu}_\mu)$ which had the form $I_\nu = 4.8\times10^{-2}\,E^{-3.0}\ \text{cm}^{-2}\,\text{sec}^{-1}\,\text{sr}^{-1}$ in the vertical direction above 1 BeV. The detailed angular distribution was taken into account. For elastic events,

$$\bar{\nu}_\mu + p \to n + \mu^+ \text{ and } \nu_\mu + n \to p + \mu^-,$$

produced by neutrinos above 1 BeV, we would expect 0.3 event in the period of this observation.[7] Information on the neutrino flux is less well known below 1 BeV because the associated muons are absorbed in the atmosphere. However, it is estimated that the contribution arising from these neutrinos is <0.3 event. In making this calculation, we assume that the muon receives, on the average, $\frac{1}{2}$ the neutrino energy. The expected rate of inelastic events was calculated assuming the cross section is given by

$$\sigma_{\text{in}} = 0.4\times10^{-38}\,E_\nu\ \text{cm}^2 \quad (E_\nu \text{ in BeV}).$$

This cross secion is consistent with the work of the CERN bubble chamber group.[8] Inelastic events should contribute 0.8 event for neutrino energies between 1 and 10 BeV during this period. We assume here that the muon receives on the average, $\frac{1}{3}$ of the neutrino energy.

We conclude that if the seven events of Table I were all due to neutrinos, then either the neutrino flux is higher than anticipated or the interaction cross section rises more rapidly with energy above the region investigated by the accelerator groups. The combination of these effects would have to amount to a factor of five or six to remove the discrepancy between predictions and observation, setting aside the very real possibility of statistical fluctuations.

The events of Table I are consistent with isotropy in the laboratory system and show no correlation with sidereal time.

We wish to express our appreciation to Mr. A. A. Hruschka for his advice and help in designing and constructing the equipment and the laboratory facilities deep underground. Mr. Bruce Shoffner was most helpful in the design and construction of the electronics. We are grateful to the directors of the Rand Mines and their consulting engineers F. G. Hill and M. Barcza and the general manager of the East Rand Proprietary Mines and his staff for providing us with the underground laboratory.

Note added in proof.—If form factors are taken into account for elastic reactions, the muon received typically 0.8 of the neutrino energy rather than the 0.5 used in this Letter. Regarding the inelastic contribution, recent data from CERN indicate that on the average, the muon gets 0.5 of the neutrino energy rather than the 0.33 used above. If we re-evaluate the expected rates with these numbers, we obtain 0.5 (elastic >1 BeV), 1.2 (inelastic 1 to 10 BeV), or a total of 1.7 events expected during the period reported. Since the CERN data can be interpreted to imply a more rapid rise than linear in the inelastic cross section, it is conceivable that the discrepancy between observation and prediction can be explained in this way. We wish to thank Professor H. Faissner for a discussion of these points.

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*Work supported in part by the U. S. Atomic Energy Commission.

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[2] The first neutrinolike event was reported by the Case-Wits group in the Proceedings of the Informal Conference on Experimental Neutrino Physics, CERN, 1965 (to be published).

[3] Proceedings of the Eighth International Conference on Cosmic Rays, Jaipur, India, December 1963, edited by R. R. Daniels et al. (to be published).

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[5] S. Miyake, private communication.

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CHARGE CONJUGATION, DECAY OF VECTOR MESONS, AND SU(6) SYMMETRY

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In this note we introduce a charge-conjugation operator in the SU(6) symmetry[1] which reproduces the usual charge-conjugation properties of known elementary-particle states, and we treat vector-meson decays into two mesons with the requirement that this operator be conserved. Interesting predictions between decay amplitudes are obtained in good agreement with the experimental data.

For any SU(3) particle multiplet, expressed in tensorial notation as $M_{BD\cdots}{}^{AC\cdots}$ $(A,B\cdots = 1,2,3)$, the usual charge conjugation is known to be equivalent to transposition of indices[2]

$$M_{BD\cdots}{}^{AC\cdots} \to \eta \bar{M}_{AC\cdots}{}^{BD\cdots}, \tag{1}$$

apart from the appearance of a common phase factor η, where $\{\bar{M}_{AC\cdots}{}^{BD\cdots}\}$ is the conjugate representation of $\{M_{BD\cdots}{}^{AC\cdots}\}$. This operation—the transposition of indices—which can be defined in any semisimple Lie group corresponds to the transformation of the states of a representation to the states having opposite eigenvalues for all the operators in the group,[3] the representation itself going into the conjugate representation. In the following, this operation will be called G conjugation.

For a multiplet which goes into itself under charge conjugation, η is the characteristic number $\mathfrak{C}$ introduced by Gell-Mann.[4] Mathematically the appearance of η in (1) is allowed by the fact that the G conjugation is defined up to a phase for the bases of representation and physically by the fact that other quantum numbers not contained in SU(3) (like baryonic number, spin, parity) are required for the complete description of the particles in the multiplet concerned.

Due to the SU(3)⊗SU(2) decomposition of the SU(6) symmetry, G conjugation of SU(6) representation induces G conjugation on both the SU(3) and the SU(2) parts constituting it. It follows from the special properties of SU(2) that G conjugation in this group, contrary to the other unitary groups, is a linear operation which can be carried out by means of the operator $e^{i\pi S_2}$, S_2 being the second component of ordinary spin, so that the phase is fixed in the G conjugation of the SU(2) part of the above decomposition. The phase appearing in the G conjugation of