though many of these monopole excitations involve muonic states with $n>3$ and low orbital angular momentum, they may be detected by γ-coincidence techniques. We feel that the method employed by Jenkins, Powers, and Kurselman[5] would not be sufficiently sensitive for the cases considered here.

A complete and detailed discussion of all of the resonances investigated is in preparation.

The extensive numerical calculations carried out in support of this investigation were done on the Honeywell GE 635 computer at the University of Kansas Computation Center.

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Zenith-Angle Dependence of Cosmic-Ray Muons*

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The zenith-angle distribution of high-energy cosmic-ray muons has been further investigated using a sample of 2×10^5 muons observed in the Utah underground detector. The data have been analyzed in such a way that the angular dependence can be extracted without substantial sensitivity to the parameters of cosmic-ray phenomenology. The zenith-angle distribution is flatter than expected on the basis of muon production via pion and kaon decay. An isotropic component (of unspecified origin) is required which rises to a maximum contribution of about 0.5 of the vertical intensity in the muon energy range 1-3 TeV and thereafter decreases.

The Utah group has previously published evidence indicating an anomalous zenith-angle dependence for cosmic-ray muons observed at depths in excess of 2×10^5 g/cm^2.[1-3] In this Letter, we present a new analysis based on an order of magnitude more data than were then available. The methods of analysis have been revised in such a way that the anomaly is more visible and the result is almost completely independent of the parameters of cosmic-ray phenomenology. In addition, vertical muon intensity measurements by Cassiday, Gilbert, and White[4] provide an absolute depth intercalibration which permits inclusion of vertical intensity data from a world survey in the analysis. When this is done, meaningful results may be extracted to a slant depth of 8×10^5 g/cm of rock. The main result is greatly strengthened evidence for the existence of an isotropic component in the zenith-angle distribution. Our conclusions depend very little on the primary spectral slope, rate of muon energy loss, fluctuations in energy loss, or, if we choose to delete the vertical-intensity data from the analysis, upon the rock density either.

The apparatus has been previously described in detail.[5-7] To trigger the apparatus and be accepted for scanning, a particle must have a minimum energy of 2 GeV and must have traversed at least 10 geometrical mean free paths of matter in a straight line. Because of the irregular mountainous overburden, the effective slant depth of the rock varies considerably for a given zenith angle as a function of azimuth angle, with the result that the muon intensity can be explored over a fairly wide range of zenith angle θ and slant depth h.

Each muon satisfying fiducial criteria was assigned to a bin corresponding to given values of h, θ. The number of muons in each bin was corrected for detector efficiency, in turn derived from analysis of the way in which events passing through several Čerenkov detectors triggered the system. Data in bins within $\Delta h/2$ of a given central slant depth h were then combined, after correcting the numbers by the ratio of the intensity at the depth for the bin to that at the central depth. The muon intensity was obtained by dividing the corrected number of muons by the appropriate area-solid-angle factors and by the running time.

In the usual picture of muon production,[8] muons originate from the decay of secondary pions with some admixture of kaons. The angular distribution which results from the process becomes proportional to $\sec\theta$ at high energies. (The enhancement with angle arises from the fact that decay competes more favorably with nuclear interaction at wider angles where the particle spends a longer time in rarified atmosphere.) We choose to fit our results with a function of the form

$$I(h, \theta) = I_{\pi K}(h) G(h, \theta) + I_X(h).$$

The first term represents the distribution arising from the usual π-K-meson decay picture, with $G(h, \theta)$ defined as the ratio of slant to vertical intensity for the meson-derived muons. Both $I_{\pi K}$ and I_X are treated as adjustable parameters in fitting the data. One may interpret I_X either as the rate for an unknown isotropic production process or as a measure of how well the data can be fitted by the conventional model.

We wish to emphasize the importance of writing the conventional prediction in this factored form. Although both $I_{\pi K}$ and G are dependent on details of muon production and energy loss, all of the sensitive dependence is contained in $I_{\pi K}$. An example of the degree of sensitivity of $G(h, \theta)$ to these details is shown in Table I. Calculations of $G(h, \theta)/\sec\theta$ are presented at a typical depth over an extreme range of the parameters entering into the calculation; it is evident that only a drastic variation in the assumed K/π ratio has any appreciable effect. Thus, $G(h/\theta)$ may be taken as exceedingly well-known without pretending any great knowledge of the phenomenology.

Some of the results from slant depths up to 7.2×10^5 g/cm^2 are presented in Fig. 1. The data are from a run of 8 months, during which time 2×10^5 muons entered the useful aperture. The solid points on each graph are the muon intensities obtained in the way described above. Each graph refers to a particular depth cut, corresponding to a particular muon energy threshold. The solid lines are fits by the function discussed above with $G(h, \theta)$ calculated assuming a 20% kaon admixture. Since the function is very nearly linear in $\sec\theta$, it is convenient to display the intercept I_X by extending the curves to $\sec\theta = 0$.

In Fig. 2(a), we have plotted the ratio of I_X to

TABLE I. Sensitivity of $G(h, \theta)$ to the parameters of cosmic-ray phenomenology at $h = 3.2\times 10^5$ g/cm^2. The "normal" parameters assumed were $\gamma = 2.7$ for the integral primary spectral index, $b = 4.0\times 10^{-6}$ cm^2/g for the coefficient of the energy-dependent term in the rate of muon energy loss, $C_K/C_\pi = 0.13/0.87$ for the ratio of the number of charged kaons to charged pions among the secondaries [$\frac{1}{5}$ for (all kaons)/(all pions)], and muon survival probabilities in standard rock as calculated by Mason (Ref. 9). In the third column, Mason's survival probabilities were replaced by a step function at an average energy E_a calculated with the given value of b. The perturbation of b was done in conjunction with that of the survival probabilities as a matter of convenience. $G(h, \theta)$ becomes more insensitive to perturbations in all parameters as h increases.

		$G(h, \theta)/\sec\theta$			
$\sec\theta$	"Normal" parameters	$\gamma = 3.2$	Step-function survival probabilities	Step-function survival plus $b = 5.0$	$\frac{C_K}{C_\pi} = \frac{0.70}{0.30}$
0.0	1.134	1.140	1.110	1.094	1.324
1.0	1.000	1.000	1.000	1.000	1.000
2.0	0.916	0.912	0.927	0.936	0.825
3.0	0.852	0.846	0.871	0.885	0.710
4.0	0.801	0.793	0.824	0.842	0.627

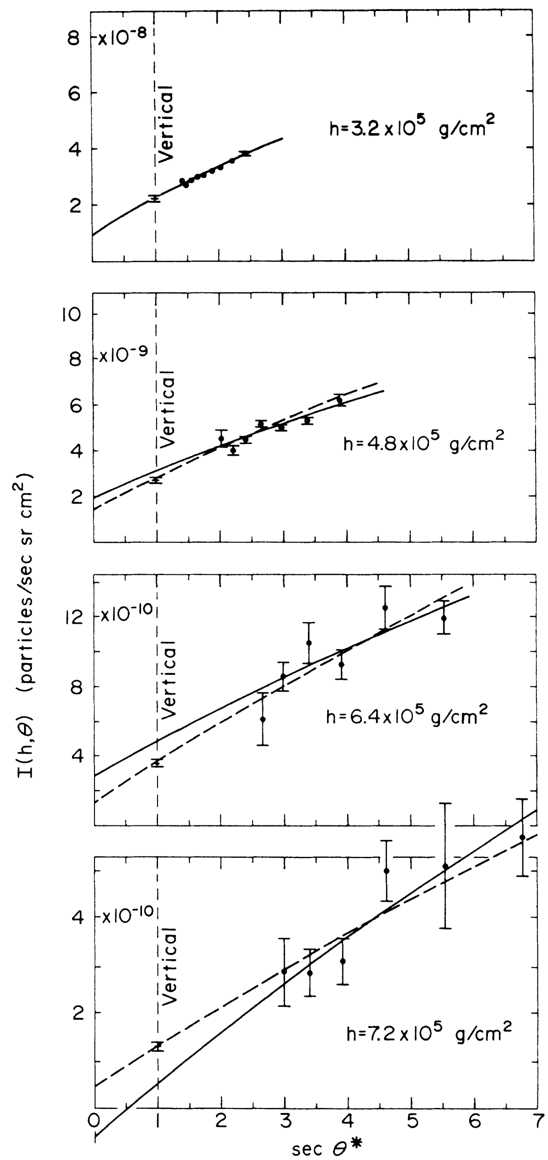

FIG. 1. Representative zenith-angle distributions at several constant slant-depth cuts, with $\Delta h/=0.8\times10^5$ g/cm^2. Counting errors only are indicated. The solid curves are fits to Utah data alone, while dashed curves include the indicated points interpolated from the world survey data.

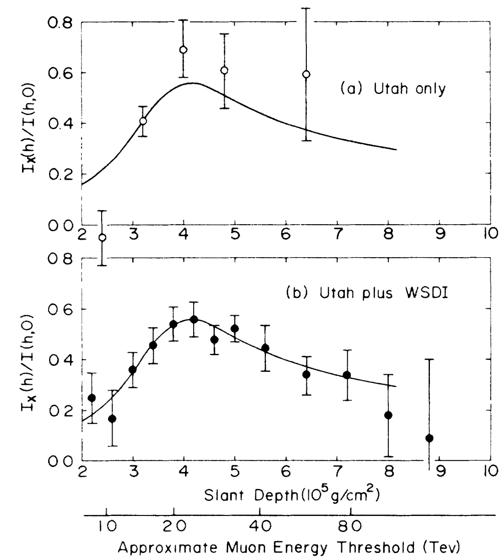

FIG. 2. Ratio of the isotropic component to the vertical intensity. The indicated errors include the effects of rock density fluctuations. Since a parametrized WSDI was used in (b), some correlation between points exists.

the total vertical intensity, $I(h,0)=I_{\pi K}+I_X$, at several depths. An approximate muon threshold energy scale is also shown. Except at the extremes, these independent fits indicate an isotropic component significant by 3 to 5 standard deviations.

Koshiba[10] has found evidence for a large number of kaons in the forward cone in high-energy primary cosmic-ray collisions, and has advanced the hypothesis that ultrahigh-energy collisions result in copious φ production via an isobar mechanism. 70% is a highly optimistic estimate of the maximum kaon fraction possible from such a process. We have made fits of the sort discussed above with this kaon fraction, and obtain a plot similar to Fig. 1(a) with I_X still nonzero by 2 to 4 standard deviations. Even pure φ production is thus insufficient to produce the degree of flattening we observe.

We have investigated rates at different azimuthal angles at fixed zenith angle and depth for a variety of depths. The results indicate depth fluctuations of 1.4% from the nominal values,[3] a number also obtained by Cassiday, Gilbert, and White[4] and consistent with density variations expected for the local geology. Except at the extremes of the curves, the data points shown in Fig. 1 contain contributions from many different directions, so that such fluctuations tend to cancel. The elimination of the extremal points from the analysis does not substantially affect the results. In any case, good statistical fits to the data are obtained when the density fluctuations are taken into account.

Previous estimates of the average density[11] and hence the slant depth of the overburden were uncertain by several percent. Conclusions based upon the Utah data alone were unaffected by this fact. However, it is evident from the lower graphs in Fig. 1 that a great deal more could be learned if vertical intensities interpolated from the world-survey depth-intensity data (WSDI) could be included in the analysis. Using a counter telescope to obtain the vertical intensity at ten locations in the access tunnel to the large detector, Cassiday, Gilbert, and White[4] have provided the required intercalibration and found a density of 2.55 ± 0.04 necessary to obtain agreement with the WSDI. Depths reported in this Letter are calculated for this density.

The result of including the world-survey data in the analysis is indicated by the dashed lines in Fig. 1 (in some cases indistinguishable from the solid lines), and the ratio of I_X to the vertical intensity from these fits is plotted in Fig. 2(b). Except at the greater depths, the ratios shown in Fig. 2(b) were made with depth cuts of width 0.4×10^5 g/cm^2 in order to minimize the errors made in correcting intensities for the central depth. Our main results concerning the existence of I_X and the general behavior of $I_X/I(h, 0)$ are unchanged by the inclusion of the WSDI, but the errors are smaller and the details better established. We may conclude that $I_X/I(h, 0)$ rises to a maximum of about 0.5 near $h = 4 \times 10^5$ g/cm^2 ($E_\mu \geq 2$ TeV), and thereafter apparently decreases. The decrease may be an artifact induced by uncertainty in the WSDI at depths greater than 5×10^5 g/cm^2, but at least the ratio does not rise.

The increasingly unsuccessful competition of meson decay with interaction at higher energies asymptotically produces a $1/E$ factor in the spectrum of muons produced by this process. It is therefore noteworthy that $I_X/I(h, 0)$ does not appear to approach unity, as it would if the isotropic intensity were not also reduced by at least an additional factor of E.

An attempt was made to fit the data with a simple model in which the isotropic muons result from decays, into a muon and another particle of small mass, of parents with a differential energy production spectrum which has a step threshold at E_0 and then falls as $E^{-\delta}$. The solid curve in Fig. 2 represents the best fit to the data, obtained with $E_0 = 1.9$ TeV and $\delta = 4.8$. There is thus some evidence for a threshold and a spectral index which exceeds the primary spectral index by at least 1. However, the evidence for a threshold depends on the shallower-depth data where our range of zenith angles is small, and sensitivity to undetermined systematic errors could be large. For this reason we do not regard the existence of a sharp threshold to be nearly so well established as is the existence of the isotropic muon component at intermediate depths. If the parent particles are produced in pairs in nucleon-nucleon collisions, the 1.9-TeV threshold implies a mass $m_X \approx 45$ GeV for the parent. One may also infer $\tau_X < 10^{-7}$ sec and a production cross section $\gtrsim 0.3$ mb/nucleon.

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