sition is essentially pure $E2$.

McGowan, Sayer, and Stelson[11] have performed directional correlation measurements on ^{152}Sm in the Coulomb excitation of the $2^{+\prime}$ level. Their preliminary results indicate the $2^{+\prime} \to 2^+$ transition in ^{152}Sm is either about 80% $M1$ or 100% $E2$. Unforunately, they do not get the A_4 term. Since ^{152}Sm and ^{154}Gd are very similar in nuclear structure (both have 90 neutrons and are at the beginning of the deformed nuclear region), one is inclined to assume that the $2^{+\prime} \to 2^+$ transition in ^{152}Sm and the one in ^{154}Gd are both essentially pure $E2$. From the standpoint of obtaining a consistent Z_0 value, it should be emphasized that the 80% $M1$ result is just as bad as, if not worse than, the 100% $E2$ result.

This leaves unanswered the problem of the inconsistency[4,5] of the Z_0 mixing parameters. Our results are consistent with the first prediction of Bohr and Mottelson[6] that the radiations are essentially $E2$. If one combines the mixing-parameter[4,5] work with our work, however, it appears then that the characterization of these rotational states built on the low-lying 0^+ states in ^{152}Sm and ^{154}Gd as symmetric vibrations in the quadripole field of the nucleus is not correct and a new description of these vibrational states is needed.

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EVIDENCE FOR A NEW PRODUCTION PROCESS FOR 10^{12}-eV MUONS*

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In the course of a preliminary study of muon backgrounds with the University of Utah neutrino detector, the intensity of cosmic-ray muons has been measured as a function of depth and zenith angle. Slant depths from 2000 to 8000 hg/cm^2 (1 hg $= 10^2$ g) have been studied corresponding to muon energies from 10^{12} to 10^{13} eV. Because of the rugged mountainous overburden, contours of equal slant depth span a considerable range of zenith angles as the azimuth is varied. At a given zenith angle θ, we find excellent agreement with the currently accepted dependence of intensity on depth. However, we find almost no variation in intensity with zenith angle, in strong contradiction to the $\sec\theta$ enhancement expected if these muons are the progeny of pions and kaons. At these energies most pions or kaons undergo nuclear interaction. Consequently, they have a better chance to decay in the rarer atmosphere encountered at the larger zenith angles.

The detector has been described by the Utah group.[1-3] Briefly, the trajectories of muons are determined by an array of cylindrical spark counters, each counter being in the form of a 15-cm-diam steel pipe with a wire down the center. The counters are pulsed, a trigger being provided by a fast coincidence between two water-filled Cherenkov counters. The sparks are located along the axis of the counter by a sonic technique to a precision of a few millimeters, and many sparks can be recorded with good efficiency in a single counter.

The coordinates of each spark are recorded in digital form on magnetic tape along with pulse-height information from the Cherenkov counters and certain auxiliary data.

For the present experiment the detector was comprised of nine columns of 40 counters each, together with two Cherenkov tanks—essentially the right-hand portion of the detector shown in Fig. 2 of Keuffel and Parker.[1] The sensitive area, normal to the counters, was 6×10 m^2 and the thickness was about 6 m. The minimum energy for a muon to be recorded was about 2 GeV, and it must have traversed ~10 geometrical free paths of concrete and iron in a straight line. The detector was located at a depth of 1850 ft in a mine at Park City, Utah.

The factors entering into a determination of the muon intensity $I(h, \theta)$ are the following:

Topography.—The slant depths for trajectories of given zenith and azimuth θ and φ were read graphically from radial profiles of the terrain surrounding the detector. The profiles were prepared using U. S. Geological Survey topographic maps with 40-ft contour intervals said to be reliable to ±5 ft; the over-all accuracy of our slant depths is estimated at ±20 ft. The survey was carried out at 2.5-deg intervals in θ and 5-deg intervals in φ, and each 2.5×5-deg^2 bin was assigned an effective depth $\bar{h}$ (differing slightly from h at the center) in such a manner that all the muons with the bin could be regarded as having traversed a thickness $\bar{h}$ from the top of the atmosphere. In calculating the $\bar{h}$ values, the logarithmic slope of the muon intensity versus depth was taken as a first approximation from the currently accepted depth-intensity curve. Since our depth-intensity curves agree with the previous picture at all θ, no iteration of this procedure was necessary. Where irregularities of the terrain were severe, the bin was broken down into four parts, and $\bar{h}$ was calculated from a suitably weighted average of the $\bar{h}$'s for the smaller bins. We estimate the accuracy in $\bar{h}$ to be ~2-3 % for the individual bins with no systematic tendency towards large or small values.

Composition of the rock.—The geology of the Wasatch Mountains is rather well known as a result of intensive mining operations. There are four basic rock formations in the region, with densities ranging from 2.40 to 2.66 and Z^2/A ranging from 5.54 to 5.72. We took 2.47 as a weighted mean density. The mean Z^2/A of our rock is 5.65. For the present no correction has been made for the small deviation from standard rock ($Z^2/A = 5.5$) now used in cosmic-ray work. The over-all precision of our depth measurements, including errors due to topology, density, and composition of the rock, is estimated as ~3 % when averaged over a number of bins in different directions.

Aperture.—An eastward- (westward-) going muon was required to pass through fiducial areas on the east (west) walls of the Cherenkov counters 1 ft in from the edges. The solid-angle area factor for each 2.5×5-deg^2 bin was calculated from the formula $d(A\Omega) = (S\sin\theta \times\cos\varphi)(\sin\theta d\theta d\varphi)$, where S is the area of the shadow of the front fiducial area cast on the rear fiducial area by parallel light incident in the direction θ, φ; the factor $\sin\theta\cos\varphi$ is the cosine of the angle between the incident direction and the normal to the fiducial planes, and the second factor is the increment of solid angle.

Triggering efficiency.—The efficiency of each Cherenkov counter was measured directly in a separate run. The fast-logic pulse from the counter under test was recorded by means of a marker code on the magnetic tape, but the trigger was a coincidence between the other Cherenkov counter and a third adjacent counter. This counter, the second from the left in Fig. 2 of Keuffel and Parker,[1] was not used during the main runs. The tapes for the efficiency runs were scanned for muons which were known from the spark-counter plots to have passed through the counter under test, and the inefficiency was taken as the percentage of these events not showing a marker. For muons passing through the fiducial area used to define the aperture in the main runs, the efficiency did not deviate from the mean value 0.86 by more than the statistical errors (~3 %) when studied as a function of zenith, of azimuth, or from counter to counter in either direction. The over-all two-counter triggering efficiency was then $(0.86)^2 = 0.74$.

Scanning efficiency.—The spark coordinates could be printed out and plotted in front and top views by the computer for any class of event. Starting with a sample of 500 events which were studied visually from the plots, a computer scanning program was developed which could reliably categorize events as (a) "noise" (≤ 3 sparks), (b) muons, (c) complex events (≥ 20 sparks), and (d) all others. Less than 0.1 % of all muons were lost in class (a). The computer scan for class (b) was 92% efficient as checked by visual scanning of samples. All the events in (c) and (d) were visually scanned. We estimate that <1 % of all muons were misclassified or lost.

Spark-counter efficiencies.—The efficiencies of the columns of spark counters were studied in situ by visual inspection of muon tracks for missing sparks, with the conclusion that a negligible number of muons were missed from this cause. The accuracy with which the computer-fitting program assigned the zenith and azimuth angles to muon events was also checked and found to be consistent with visual measurements; the error in assigning a zenith angle is due mainly to the finite diameter of the counters and is about ±0.5 deg.

During 2.01×10^6 sec, 14 500 muons were recorded. A tally of the number of muons in each 2.5×5-deg^2 zenith-azimuth bin constituted the raw data from which the analysis started. From this matrix those bins were selected for which the effective depth lay in a given 200-hg/cm^2 range and the zenith angle spanned a given 10-deg interval. If N is the total number of muons in such a group and $A\Omega$ the corresponding total aperture, we have $I(h, \theta) = N/A\Omega\eta t$, where η is the efficiency and t the live time. The intensities obtained in this way are plotted in Fig. 1. For clarity, the points for each successive range of θ have been shifted up by one decade. Also plotted for each θ range is a world-survey,[4] vertical depth-intensity curve $I_V(h)$ (solid lines, repeated identically for each decade), as well as the function $I_V(h) \times \sec\theta^*$ (dashed lines). (θ^* is the zenith angle at the top of the atmosphere of a trajectory whose zenith angle is θ at the detector.) It is seen that the observations are in sharp disagreement with the $\sec\theta^*$ enhancement, but that they agree very well with $I_V(h)$, particularly in view of the fact that the measurements are absolute with no normalization.

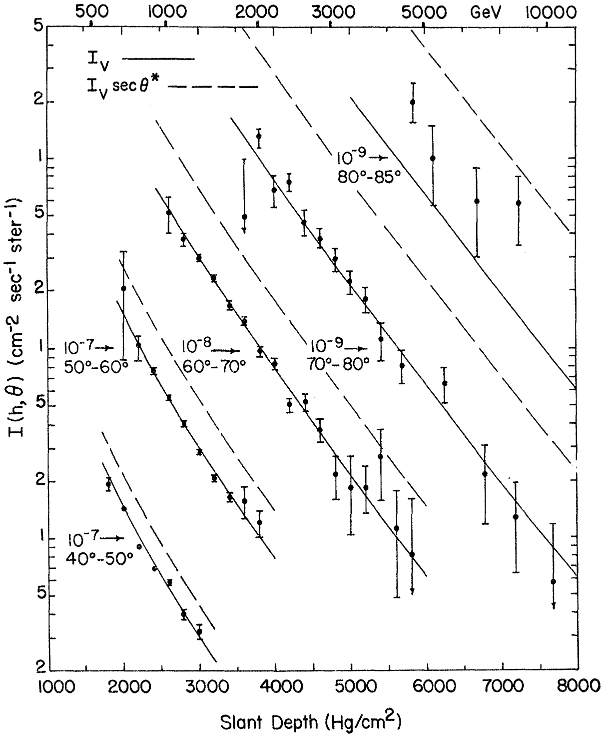

FIG. 1. Observed muon intensities $I(h, \theta)$ compared with a world-survey vertical depth-intensity curve $I_V(h)$ (solid lines) and $I_V(h) \sec\theta^*$ (dashed lines). Correction of our data to standard rock ($Z^2/A = 5.5$) would move the points to the right 0.8% at 2000 hg/cm^2 and 2% at 8000 hg/cm^2. A scale of threshold muon energies is shown at the top. Mean energies are higher by $\sim\frac{3}{2}$.

We believe that our depths are known to ~3 %. However, our most dense rock formation deviates from the mean density by only 7 %. Even if we were to suppose that all the rock were of this density, it would not change our conclusion.

Quite independently of rock density and composition and of any assumed vertical depth-intensity curve, the flat θ dependence may be inferred by plotting the observed intensities for fixed h as a function of $\sec\theta^*$. Figure 2(a) shows 5 of the 26 plots so constructed. Straight lines representing the function $\sec^s\theta^*$ have been fitted to the points on a log-log plot. Although the individual values of s obtained in this way are not very accurate, the weighted average value, $s = 0.25 \pm 0.09$, is clearly inconsistent with unity. No significant trend for s as a function of h can be discerned in the complete set of plots. Open circles at $\sec\theta^* = 1$, representing the vertical intensities from the world survey, are also shown. If lines with

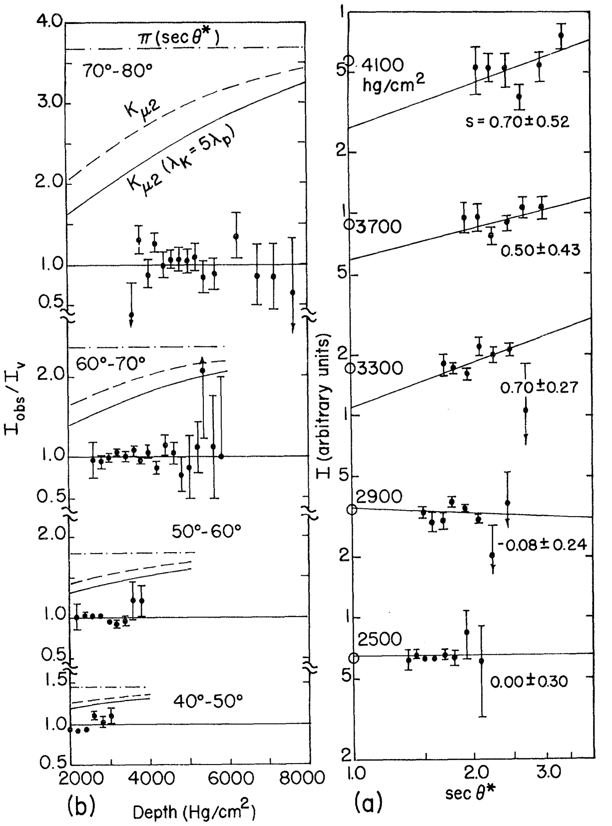

FIG. 2. (a) Observed muon intensities versus secθ^* at fixed h. The solid lines are fits to sec$^S\theta^*$. One decade horizontally equals two decades vertically. Open circles are world-survey vertical intensities. (b) Observed intensities relative to a world-survey $I_V(h)$ compared to the predictions of various models.

unity slope were forced to fit the data and extrapolated back to vertical intensities at secθ^* $=1$, there would be discrepancies up to a factor 4.

The enhancement factor for kaons is somewhat less than for pions, especially at the lower end of our energy range, because of the shorter kaon mean life and smaller time dilatation factor at the same energy. The factor for the extreme case of all-$K_{\mu 2}$ parentage, obtained from the standard work on the subject by the Cornell group,[5] is shown in Fig. 2(b), where to facilitate comparison we have plotted the ratio $I(h, \theta)/I_V(h)$ for the observed points and for the curves predicted on the basis of various models. Along with the all-π curve (dots and dashes) and all-$K_{\mu 2}$ curve (dashed line), we have also plotted the enhancement prediction for a model where the kaon parents are assumed to have an absorption mean free path of 5 times the absorption mean free path of the primary cosmic rays. Our data are in gross disagreement with even the most extreme of these models.

The disagreement can only be accentuated if scattering produces much of an effect. We believe that this effect is negligible in our experiment, except perhaps in the 80- to 85-deg region. However, we do not at present have confidence in our ability to analyze points beyond 80 deg and do not attach any special significance to them.

It is to be emphasized that the secθ enhancement is a fundamental consequence of the competition between decay and interaction of pions and kaons produced by cosmic-ray primaries incident on an exponential atmosphere. Pions (or kaons) from inclined primaries are produced on the average at higher altitudes and encounter rarer air than those produced vertically. The instability of the muon requires that it be a product of the primaries; the decay properties of π and K are well known; and although the nuclear interaction paths of these particles at high energies are uncertain, we have seen that the predictions are insensitive to the absorption free paths.

We therefore conclude that the majority of cosmic-ray muons of energy $>10^{12}$ eV are produced either directly or as the progeny of a parent which decays copiously into muons with a mean life much shorter than that of the kaon.

While the effect is well established, a determination of the fraction of muons still coming from pions and kaons at various muon energies must await longer runs with the full apparatus and a more detailed rock survey. It should be pointed out, however, that the number of muons produced by the new process in high-energy collisions still need not be a very large fraction of the number of pions—both because of the small chance that the pion should decay (1/11 at 1000 GeV) and because the majority of pions coming from the fireball have a low energy. The steepness of the cosmic-ray spectrum strongly favors processes which retain a large fraction of the primary energy.

The foregoing considerations, plus the fact that we are probably dealing with primary interactions towards the upper energy limit of direct emulsion observations, make it appear unlikely that the new process would have been detected in emulsion work. It would seem very important to look in emulsions not only for muons but also for energetic electrons (which would be expected if an intermediate boson were being produced).

Previous work on the angular distribution of underground muons has given some hint of the effect we report. A summary of previous investigations is given along with their own results by Achar et al.,[6] who comment on a rather higher exponent in a $\cos^n\theta$ type of analysis than would be expected from pion and kaon parents. An enhancement factor slightly smaller than $\sec\theta$ has been found by Barton and Stockel.[7] As compared with previous work, our experiment has the advantages of large area, detailed identification of the muons, and especially the variable overburden afforded by the mountainous terrain. Other large neutrino detectors are too deep for these studies.

Early work on the temperature effect of underground muons,[8] although involving a statistical analysis of a 1% effect, appeared to support the usual picture of pion and kaon parentage of the muons at 1500 hg/cm^2 depth.

Supporting evidence that muons in the range 1000-4000 GeV are produced by pions with roughly a 20% admixture of kaons has been obtained from a comparison of the sea-level muon spectrum, as inferred from the flux of γ rays at high altitudes, with the sea-level spectrum inferred from underground muon measurements.[9] The comparison depends on a calculation of the losses from photonuclear interactions by the virtual photons of the muon's Coulomb field; the photonuclear cross section is assumed to remain constant for two decades beyond accelerator energies. However, a reconciliation of the γ-ray data with the flatter spectrum implied by direct muon production seems to demand a higher nuclear interaction cross section at very high energies. The flatter spectrum and greater cross section also seem to be required by the horizontal air shower observations of the Tokyo group[10] and by some (but not all) burst observations.[11] Additional work along these lines, both theoretical and experimental, is obviously highly desirable.

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