Vertical Muon Intensities at the Utah Site*

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In order to test the possibility of explaining Utah's observed underground muon deficit at large zenith angles on the basis of rock density anomalies, a portable cosmic ray telescope was set up at five different locations under the beam line of the large Utah neutrino detector. The main rock density above each station could be accurately inferred from the observed vertical intensity. If the resulting values are incorporated into the Utah data, the existence of an isotropic muon component, as inferred from the Utah extrapolations, seems to be substantiated.

Observations performed with the Utah neutrino detector[1-3] have indicated that cosmic-ray muons do not show the full $\sec\theta$ enhancement which would be expected if their parents were pions and kaons produced in the upper atmosphere. In order to explain the observed underground muon angular distribution, an isotropic production mechanism, termed the X process, has been postulated. In order to test whether this effect could be due to some rock density anomaly, muon intensities were measured at five different locations under the beam line of the Utah detector using a mobile cosmic-ray telescope. The observed rates, together with a world-survey depth-intensity curve (WSDI), establish the bulk density of the Utah rock in a direct way. Once the uniformity of the density is established and a value found, the WSDI provides an absolute vertical reference for the Utah experiment. By comparing the Utah vertical intensities (obtained by an extrapolation of their inclined measurements) with those obtained from the WSDI, a sensitive overall check can be made on the validity of the Utah results.

The procedure adopted for measuring the rock density involved the comparison of the rates measured underground with those obtained from a calculation using the density as an adjustable parameter. A value for the density is obtained by forcing the calculated rates to agree with the measured rates.

The measured rates contained contributions from zenith angles up to 45° (however, most of the contributions were within 25° of the zenith). Thus, the calculated rate involves an integration over these zenith angles as well as 360° in azimuth. The expected rate is

$$R=\int I(h(\theta,\varphi),\theta)A(\theta,\varphi)\,d\Omega,$$

where $I(h(\theta,\varphi),\theta)$ is the muon intensity for a slant depth h and zenith angle θ and $A(\theta,\varphi)\,d\Omega$ is the detector aperture for a particular θ,φ direction. Note that h is written as an explicit function of θ and φ. These depths are obtained in feet from topological survey maps and are converted to grams per square centimeter using the rock density ρ. We have written the muon intensity in the form $I(h,\theta)=I_v(h)f(h,\theta)$, where $I_v(h)$ is obtained from a fit to the WSDI in the depth interval 0.9×10^5 g/cm^2 to 2.5×10^5 g/cm^2. A Z^2/A correction, which converts standard rock depth to equivalent Utah rock depths, has been applied, although in this depth interval the correction is less than 0.5%. The angular distribution $f(h,\theta)$ is based on the work of Barrett *et al.*[4] but has been modified to include the effects of both pions and kaons. The above slant-depth interval corresponds to a muon energy interval of 0.2 to 1.0 TeV. Since these energies are below the X-process threshold, its effect is not included in $f(h,\theta)$. Indeed, at these depths and angles, $f(h,\theta)$ is primarily dependent upon pions alone, with kaons causing a modification in $f(h,\theta)$ of about 2% at most at the extreme limits of the aperture. Thus the overall integral value is virtually independent of a choice of model for calculating angular dependencies. The function $A(\theta,\varphi)$ is the overlap area of the active elements of the telescope.

The apparatus consisted of three parallel planes of scintillation counters arranged to form two telescopes. The basic trigger for each telescope was a three-fold coincidence. A double discrimination technique was employed to monitor counter stability. Sandwiched about each counter was enough lead and iron absorber to inhibit anomalous triggers due to knockon electrons. A check on the effectiveness of this arrangement was made by using the telescopes as a trigger for three layers of cylindrical spark counters.[5] From a visual scan of the resulting printout, it was determined that the knockon contamina-

TABLE I. Tabulation of muon rates and resultant rock densities as a function of distance from the main Utah neutrino detector. Two errors are quoted for each measured muon rate. The error in the upper line is the statistical error for the measurement. The error in the lower line results from the statistics of the fit used for the WSDI as well as our best estimate of systematic errors. The densities were obtained by forcing agreement between the observed and estimated muon rates.

Muon Rate ± experimental error / calculational error (No. muons/day)				Density ρ (g/cm³)	
Channel		1R	1L	1R	1L
Location	Distance from Main Detector in Meters				
1	0	24.5 ± 1.0 ± 1.2	38.3 ± 1.3 ± 1.8	2.48 ± .05	2.57 ± .05
2	375	49.1 ± 1.0 ± 2.4	47.2 ± 1.8 ± 2.3	2.57 ± .05	2.51 ± .05
3	1,980	184.0 ± 14.0 ± 14.0	158.0 ± 13.0 ± 11.0	2.58 ± .09	2.49 ± .09
4	1,190	110.9 ± 5.4 ± 6.8	100.6 ± 5.2 ± 6.0	2.55 ± .06	2.56 ± .08
5	750	45.6 ± 2.0 ± 2.2	71.6 ± 2.5 ± 3.8	2.61 ± .05	2.55 ± .05
				Weighted Average $\bar{\rho}$ = 2.55 ± .04	
				χ^2 = 5 (for 10 data points)	

tion was no more than about 1.5 to 2.5% per channel. Another estimate of the knockon contamination was made by continually monitoring the sum of the two threefold channel recordings with the OR combination of the two. This estimate closely agreed with that obtained by the visual check and, consequently, the rates measured for each detector location were corrected by the appropriate amount.

Rates were measured at five different locations underground, the two different threefold apertures each centered roughly upon a zenith angle of about 15° in diametrically opposite azimuthal directions. This permitted sampling of ten different regions of rock beneath the beam line of the main Utah detector in a particular azimuthal direction. (The uniformity of the rock in azimuth has already been established.[3] The rates measured at these locations, in addition to establishing the absolute value of the rock density, also provided a check on the rock uniformity.

The measured rates, associated errors, and densities obtained for the ten different rock sectors are shown in Table I. The resultant density is 2.55 ± 0.04 g/cm^3. The errors quoted in the top row of each line in the table are the statistical errors for each measurement. The errors quoted in the row below include both the statistical errors and the estimated systematic errors involved in the count-rate calculation. The major portion of the error in the count-rate calculation is contributed by the statistical errors of the various points on the WSDI. A second source of statistical error arises from slant-depth measurements made from the topological survey maps. By comparing our slant depths with those made independently by the Utah group[6] for the main detector, it was determined that the differences between the two sets of data exhibited a normal distribution with a standard deviation of about ±10 ft (about $\pm 8\times 10^2$ g/cm^2). Furthermore, based upon underground surveys performed by United Park City Mines, it was estimated that a 10-ft systematic error in depth location was possible. These errors were then incorporated in the rate calculation.

The χ^2 obtained is 5 for nine degrees of freedom. It is concluded that the observed distribution of densities is completely consistent with a statistical variation about a mean of $\bar{\rho} = 2.55$

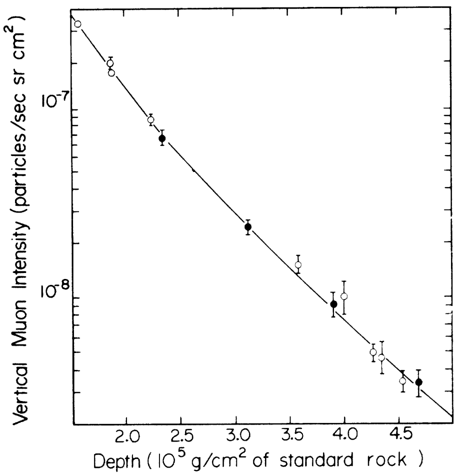

FIG. 1. World-survey depth-intensity curve. The fit used is of the form $I_v(h) = \exp(\alpha_1 + \alpha_2 h) + \exp(\alpha_3 + \alpha_4 h)$. Only the non-Utah data points (shown as open circles) have been used in obtaining this fit. The Utah extrapolated intensities are shown as filled circles.

g/cm^3 with a standard deviation of 0.04 g/cm^3. On this basis, the Utah rock is believed to be limited to random density variations of no more than 1.5%. This is in good agreement with the 1.4% rms azimuthal variation (for a fixed θ) seen by the main Utah detector.[3]

If the Utah extrapolated vertical intensities are constrained to agree with the WSDI, as discussed by Bergeson *et al*,[7] a rock density of 2.56 ± 0.02 g/cm^3 is required. Our completely independent result of $\rho = 2.55 \pm 0.04$ g/cm^3 agrees with this requirement. The resultant vertical intensities extrapolated from the Utah data for rock depths corresponding to a density of 2.55 g/cm^3 are plotted in Fig. 1 along with the WSDI points. The curve shown represents a fit of the form $I_v(h) = \exp(\alpha_1 + \alpha_2 h) + \exp(\alpha_3 + \alpha_4 h)$ to the WSDI for a slant-depth interval representative of rock surveyed in this experiment. This fit does not utilize the extrapolated Utah points. It may be seen that the Utah extrapolated vertical intensities are completely consistent with the measurements of other workers. This agreement provides a strong overall confirmation for the observed angular distribution of the Utah experiment.

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