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RE-EXAMINATION OF THE ANOMALOUS ZENITHAL DISTRIBUTION OF THE ATMOSPHERIC MUONS

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ABSTRACT

An examination of the data from the Utah neutrino detector indicates the presence of internal inconsistencies. This is shown by making comparisons among in situ data only, instead of referring them to the world survey data. The X-process proposed by Bergeson et al. seems, therefore, weakly based, if not unsubstantiated.

RE-EXAMINATION OF THE ANOMALOUS ZENITHAL DISTRIBUTION OF THE ATMOSPHERIC MUONS

According to Bergeson et al.,[1,2] the zenith angle distribution of muon intensities observed by the Utah underground neutrino detector does not show the so-called sec θ - law enhancement. This discovery has led them to propose a new production process for high energy muons which they call the X-process.[2,3] Although their results are not borne out by similar experiments,[4,5,6] and have been questioned by several cosmic ray workers,[7,8,9] speculative theories have already been advanced to explain these interesting results.[10]

It is the purpose of this letter, therefore, to point out some overlooked aspects in the Utah group's papers which would affect their conclusions.

(1) Normalization to the world survey data. One of the defects in the Utah experiment is the lack of a vertical intensity measurement at the observing site. Intensities of obliquely incident muons recorded by the underground neutrino detectors are, therefore, compared to the vertical intensities obtained at other places by different detectors, which are referred by Bergeson et al.[1,2] as the world survey data.[11] Due to the range straggling of extremely energetic underground muons, caused mostly by fluctuations in the radiation loss of muons in the ground, the intensity-depth relation, even in the vertical direction, contains a considerable uncertainty which increases with penetration depth and has been estimated by many cosmic ray physicists.[12-14] For example, the vertical intensity of 5 TeV muons (integral spectrum) ranges between 5×10^{-9} and 2×10^{-10} $(\mathrm{cm}^2\ \mathrm{sec\ ster})^{-1}$ (see Fig. 13 in Ref. 11). According to Hayman et al.[13] the upper and lower limit of the vertical muon intensity at 5000 hg/cm^2 (1 hg = 10^2 g) standard rock depth for 90% confidence is 4×10^{-9} and 8×10^{-10} $(\mathrm{cm}^2\ \mathrm{sec\ ster})^{-1}$, respectively. If we consider the statistical and experimental errors as well as these natural spreads of range of high energy underground muons, the world survey data referred to by the Utah group cannot lead to a unique depth-intensity curve. In other words, the choice of the world survey data as a substitute for a vertical muon intensity measurement in situ introduces a very crucial error which can affect their conclusions.

This kind of uncertainty can be, however, avoided by making comparisons within their own data,[15] as will be shown in the following.

(2) Normalization of the 45° data. Since the smallest zenith angle range in the Utah data is 40°–50°, we can examine the enhancement of obliquely incident muon intensities by normalizing the theoretical value at 45° to the observed average intensity in this zenithal range to the theoretical value at 45°. Theoretical calculations of the zenith angle dependence of atmospheric muons have been made by several authors.[16,18] The atmospheric muons are decay products of pions or kaons produced by nuclear interactions of primary cosmic rays with air nuclei in the upper atmosphere, and should be distinguished from the muons produced by other possible processes, such as neutrino-induced muons.[19] The solid line in Figure 1 is the theoretical atmospheric muon intensities at 45° zenith angle in the energy range from 0.5 to 2 TeV, which were calculated by extending the previous work.[18] It should be noted that in order to fit the calculated value to the observed muon intensity at 45°, the differential energy spectrum of muon parents at production, which is assumed to be of the form $E^{-\gamma}$, should have $\gamma = -2.7$ and $\gamma = -2.86$ for pion (π)- and kaon ($K_{\mu 2}$)-decay, respectively.[20] This is consistent with earlier studies done by Ashton and Wolfendale.[21]

(3) Secant θ law enhancement. According to Bergeson et al.,[1,2] the Utah results do not show any variation of muon intensity with zenith angle, in strong contradiction to the sec θ enhancement expected if these muons are progeny of pions and kaons. It should be noted that the sec θ law for obliquely incident muons, referred to by Callan and Glashow[10] as well as by the Utah group, is based on a very crude approximation which is valid only under the following conditions: (i) the energy of muons at production is far larger than the decay factor of the pion (B_π) or kaon (B_k), which is approximately 0.1 and 0.9 TeV, respectively. (ii) the energy loss and decay in flight of muons in the atmosphere is negligible. (iii) the curvature of the atmospheric layers is disregarded.

Strictly speaking, none of these conditions is satisfied for obliquely incident muons. Neglecting both the energy loss of muons in the atmosphere and the curvature of the atmosphere, the ratio of the muon intensity (integral spectrum) at zenith angle θ to the vertical intensity is given approximately by[22]

$$\frac{I(E,\theta)}{I(E,0)} = \frac{(\gamma+1)E + E_0 + (EE_0)^{1/2}/(2\gamma+1)}{(\gamma+1)E\cos\theta + E_0 + (EE_0\cos\theta)^{1/2}/(2\gamma+1)} \tag{1}$$

where the numerical value of E_0 is of the order of B_π or B_k.

Assuming that condition (i) holds, we get roughly

$$I(E,\theta) = I(E,0)\sec\theta \tag{2}$$

The energy range of the Utah observations is between 0.5 and 10 TeV, which is not large enough to neglect the E_0 and EE_0 terms in Eq. (1). Thus the enhancement of muons with zenith angle θ will not be as large as given by the sec θ law, although the actual deviation from the sec θ law will be very small, and will be masked by statistical errors, particularly at small zenith angles. On the other hand, at zenith angles larger than around 70°, the curvature of the atmospheric layers cannot be neglected. In order to take this fact, i.e. condition (iii), into account, Bergeson et al. used sec θ^* instead of sec θ, where θ^* is defined as the zenith angle at the top of the atmosphere of a trajectory whose zenith angle is θ at the detector. As shown by Maeda,[18] θ^* is a function of altitude for any given value of θ. Since there is no universally accepted definition for the height of the top of the atmosphere, θ^* must be defined more explicitly.

According to Osborne,[23] the value of θ^* is taken at such an altitude that the amount of air traversed from the top of the atmosphere along the direction of the muon trajectory to this point is 80 g/cm^2. The actual altitude of this point increases, therefore, with θ; e.g., in the U. S. Standard Atmosphere it is 18 km in the vertical direction but 21 km at 45° and 31 km at 85°. As mentioned above, intensities of atmospheric muons have been rigorously calculated without these approximations.[17,18] The results of computations made by extending previous calculations are shown in Figure 1 by the dashed- and dotted-lines for pion- and kaon-produced muons, respectively. It can be seen from this figure that the disagreement between the data points and the theoretical curves is not remarkable except at zenith angles 70°-80°. In Figure 1, the Utah data for different zenith angles are plotted separately with corresponding theoretical lines, in the same manner as in Figure 1 of Reference 1. In order to visualize the muon intensity enhancement at the same energy range with zenith angle, these results are replotted on the same scale in Figure 2, where the data for different angle ranges are indicated by different symbols. Since the difference between the calculated zenith angle dependences for intensities between the pion-produced and kaon-produced muons is small as can be seen from Figure 1, the theoretical curves in Figure 2 are drawn by assuming that the abundance of kaon-produced muons is 50% of the total intensity of muons at all energies.† The vertical intensity corresponding to these theoretical results are also shown in Figure 2 by a dotted line, while a solid line is normalized for 45° data and dashed lines stand for other angles. It should be noted that the range-straggling and angular scattering of penetrating muons in the ground are neglected in the theoretical calculations for these curves.

(4) Internal inconsistency in the Utah data. As can be seen from Figures 1 and 2, the Utah results indicate a significant enhancement of muon intensities in the oblique direction, particularly in the interval 80°-85° (where the sec θ^* approximation is not valid). Enhancements in the 50° -70° angular range are also evident though no so significant as in the 80°-85° range. On the other hand, the

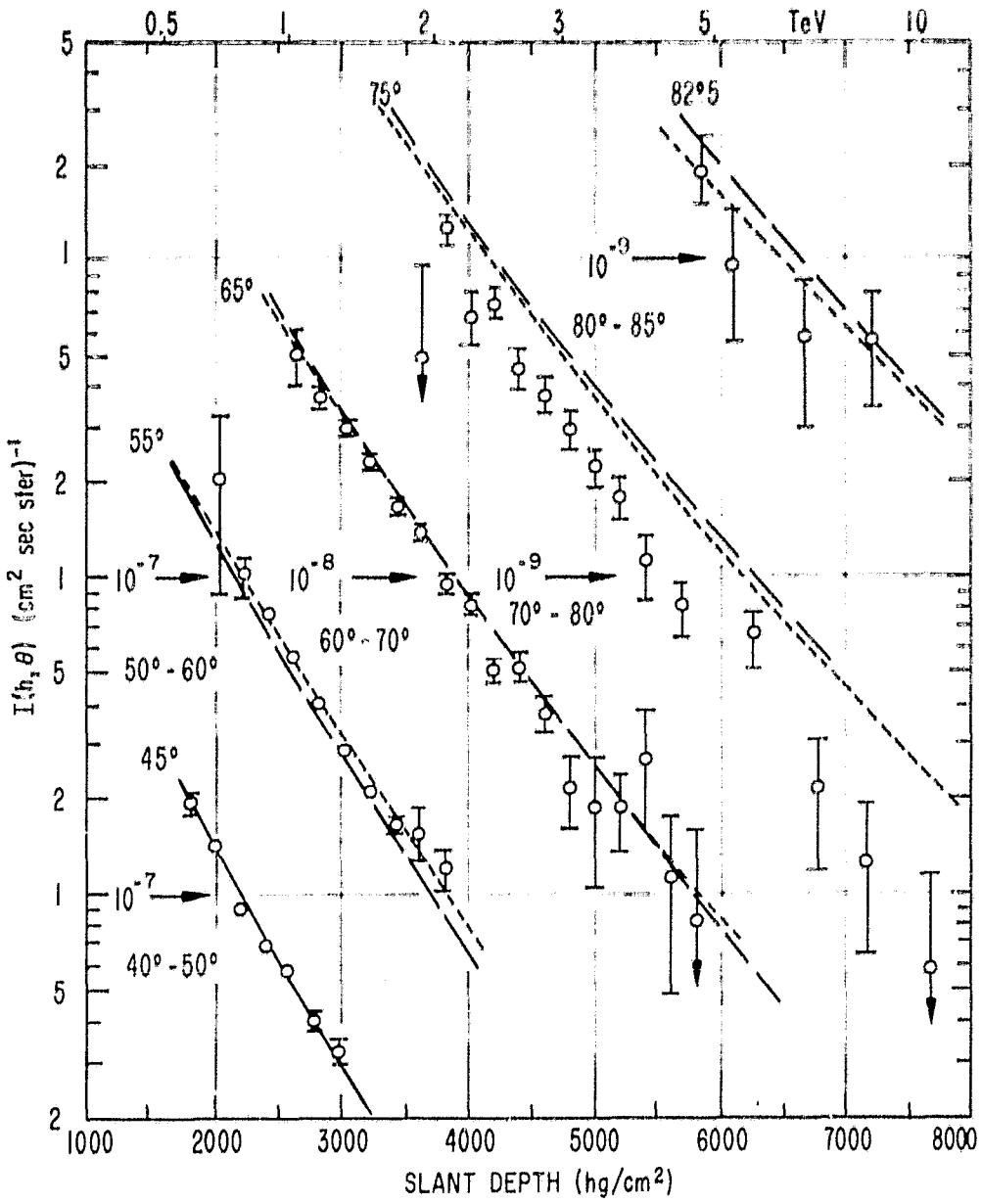

Figure 1–Comparison of the Utah data I(h, θ) and calculated intensities of atmospheric muons at depth h (in hg/cm^2), where the solid line is normalized to the Utah data at 40° - 50°, and dashed lines and dotted lines correspond to pion-produced and kaon-produced muons, respectively. The vertical scale for I(h, θ) is shifted one decade each for different angular ranges, as originally shown by Bergenson et al.[1]

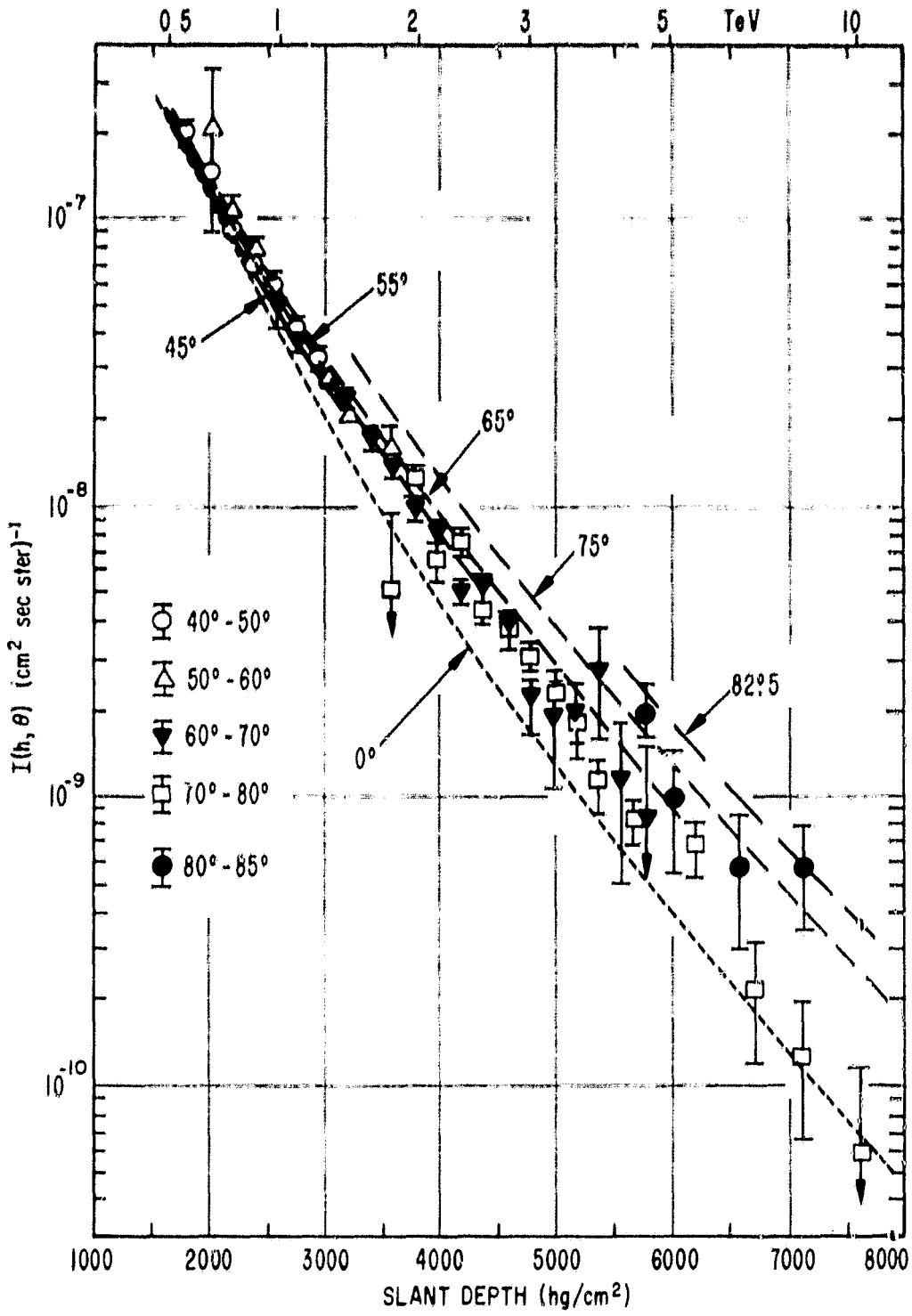

Figure 2–The Utah data, I(h, θ) and corresponding theoretical curves are plotted on the same intensity scale, where the Utah data for different zenith angles are plotted by using different symbols. The theoretical curves are calculated for 50% mixture of kaon-produced muons at all energy. The solid line, a dotted line and dashed lines stand for normalization to the Utah 40° - 50° data, the corresponding vertical intensity, and intensities at different zenith angles, respectively.

same detector has shown an anomalous depression around 75°. It should be noted that the enhancement of muon intensities at 50°-60°, 60°-70° and 80°-85° does not strongly contradict well-known production processes of atmospheric muons. In this respect, the muon intensity in the 70°-80° zenith angle direction seems to be erroneous. This matter should be resolved by future re-investigation of the details, from directional sensitivities of the detector to final data processing.

This kind of inconsistency is also shown recently by Keuffel[3] by describing the oblique muon intensity at depth, h (in hg/cm²) by

$$I(h, \theta) = I_v(h) \sec^{s} \theta \qquad (3)$$

where $I_v(h)$ is the arbitrarily assumed vertical muon intensity at the depth h. This new description still shows the zenith angle anomalies, i.e.

$s = 0.8 - 1$, for $h = 2400$, 5600 and 7200 hg/cm²,

$s = 0.3 - 0.6$ for $h = 3200$, 4000 and 48000 hg/cm², and

$s = 0.1$ for $h = 6400$ hg/cm².

These are in marked disagreement not only with each other but also with results from the similar underground observation at Kolar, India[5] where the ratio $I(h, \theta)/I(h, 0)$ is obtained by direct measurement of the vertical intensity at the equivalent depth corresponding to the slant depth, h, in the direction of zenith angle θ. Although the Kolar results are rather preliminary and might be changed somewhat by angular-depth measurements with improved accuracy, the enhancement of the muon intensity in the oblique direction does not indicate any anomaly as does the Utah experiment, ruling out even a 2% contribution of the X-process as proposed by Bergeson et al.[2]

Finally, it should be noted that one of the most accurate tests for the theory of atmospheric muons at extremely high energy regions and for the Utah X-process for production of energetic muons can be made at mountain altitudes, where energetic muons arriving from below the horizontal direction can be observed. These muons and their parent particles travel one of the longest paths in the earth's atmosphere, leading to the largest possible atmospheric effects on the muon production processes.[20]

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† Recent measurement by Nash and Flamer [6] have indicated that the kaon to pion ratio in cosmic rays is less than 0.4 at energies up to 800 GeV.