

THE CHARGE RATIO OF ULTRA-HIGH ENERGY MUONS*

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Using the University of Utah neutrino detector, which has the advantage of observing relatively low energy muons which had enormous energies at production, the charge ratio of muons with production energies greater than 1 TeV (a decade higher than previously published results) was found to range from 1.28 ± 0.05 for the lowest energy data point to 1.05 ± 0.14 for the highest. This introduces a constraint which any proposed muon production mechanism must satisfy.

The Utah neutrino detector [1-3] (Fig. 1) includes an array of 600 cylindrical spark counters (CSC's) in which the position of a muon track is determined using sonic ranging. Triggering is supplied by coincidence pulses in the Èerenkov detectors (labeled *A*, *B*, *C* and *D*). The dark shading represents the magnets in which the direction of the approximate 15.5 kG field is alternately up and down consecutive legs. This experiment is the first using the magnets of the Utah detector. The light shading in Fig. 1 is concrete.

The events are automatically stored on magnetic tape for later computer analysis and refinement on campus. The refinement includes speed of sound and temperature gradient corrections, and a "principal plane correction" in which the geometrical error incurred in locating the muon track from sparks on the centre wires of the CSC's is eliminated to first order by a transformation into the plane including the muon track parallel to the axis of the CSC's.

The charge of each muon was determined by making a least squares fit to a line bent at the centre of the magnet - the directions of motion, bending, and magnetic field determining the charge. Those events which were geometrically acceptable, free from ambiguity due to sparking, and sufficiently bent were accepted and binned as a function of charge, slant depth of rock traversed, and zenith angle. The consolidated results listed below are the closed circles plotted in Fig. 2. Also plotted is the charge ratio of all muons observed to be part of an underground muon shower. Plotting data as a function of $E \cos \mathbf{q}$ (where E is the average muon production energy and \mathbf{q} is the zenith angle of the track) was done for comparison with a simple model to be described.

The values of E for these five data points were found by matching the Utah spectrum [4] to the vertical depth-intensity relation and are somewhat larger than would be calculated from the usual range-energy relation [5]. Although a better understanding of the range-energy relation is desirable, the results presented here are rather insensitive to it.

* Supported by the National Science Foundation (U.S.A.).

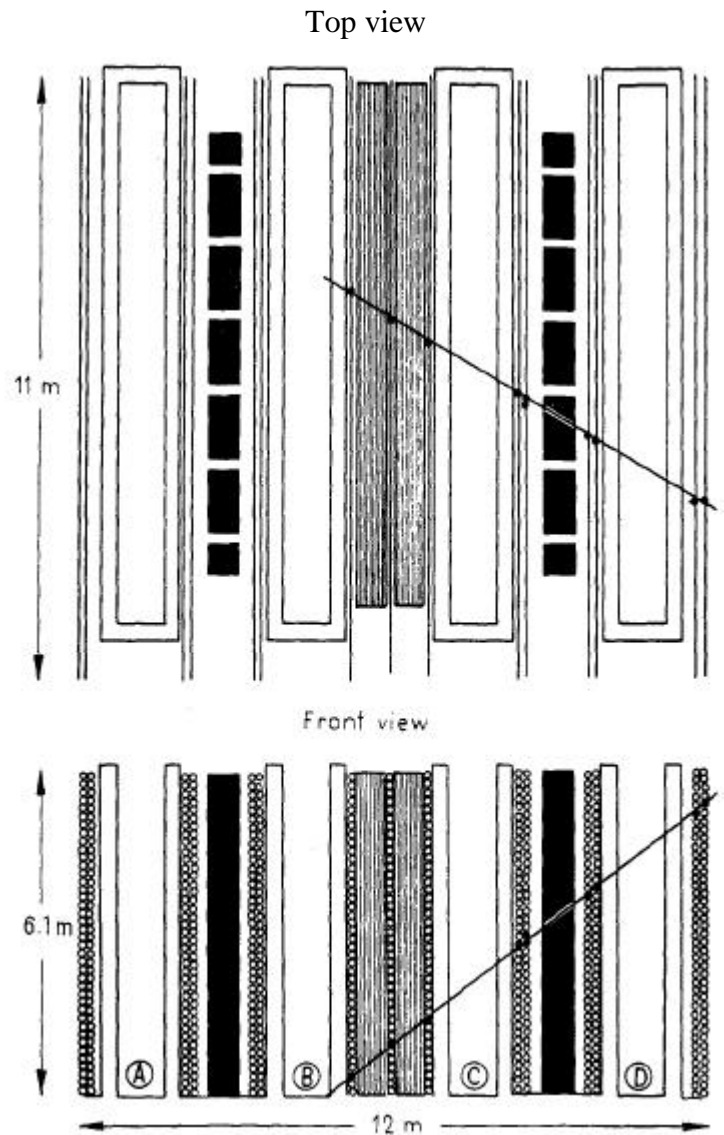


Fig. 1. Diagram of the Utah detector with a typical muon track

Positive/negative muons, zenith consolidation

| Depth (10^3 hg/cm 2) | μ^+/μ^- | Charge ratio | Average depth | Average zenith |
|--------------------------------|---------------|-----------------|-----------------|-------------------|
| 2.0—3.0 | 1666/1303 | 1.28 ± 0.05 | 2710 hg/cm 2 | 51° |
| 3.0—4.0 | 1843/1366 | 1.35 ± 0.05 | 3398 | 60° |
| 4.0—5.0 | 420/ 338 | 1.24 ± 0.09 | 4410 | 67° |
| 5.0—6.0 | 171/ 139 | 1.23 ± 0.14 | 5387 | 72° |
| 6.0—8.0 | 121/ 115 | 1.05 ± 0.14 | 7020 | 78° |

The open circles are the weighted mean of all published measurements having zenith angles close to vertical as summarized by BABER et al. [6]. There are no previous measurements of charge ratio above 1 TeV, except those measured close to the horizontal.

Error analysis included a study of events treated as though there were a magnet in place of the concrete in the centre of the detector. This revealed a small (1-2 mrad) systematic error in the bending measurements, but magnetic field alternations (alternate leg construction and current reversals) eliminate this as a source of error for the charge ratio measurement. A study of the charge ratio vs. the minimum bending accepted and also a study of muons traversing both magnets were two methods used to determine directly the fraction of positive muons mistaken as negative and viceversa. The weighted average was 0.03 ± 0.02 which is negligible here.

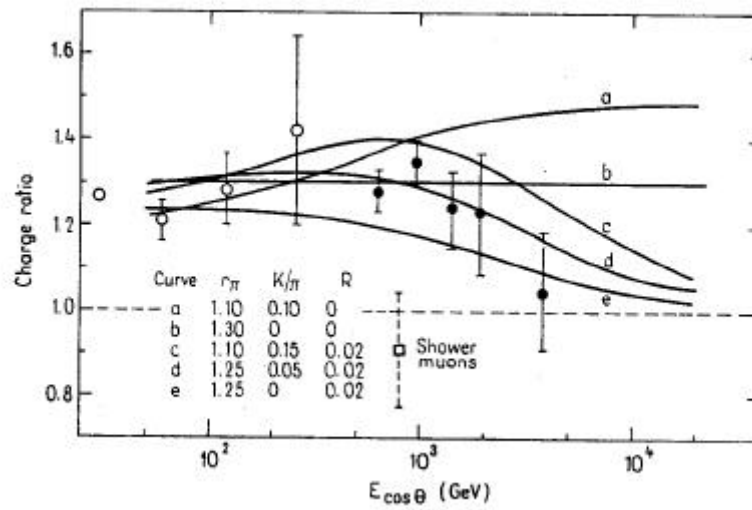


Fig. 2. Charge ratio as a function of $E \cos \theta$ for muon production energy E and zenith angle θ . Closed circles are the present results. Open circles are the weighted mean of previously published results [6]. Lines a-e are the predictions of a simple production model

Assuming muon production from pions, kaons and a direct or X-process,

$$\frac{N^+(E, \theta)}{N^-(E, \theta)} = r(E, \theta) = \frac{\frac{r_\pi}{r_\pi + 1} + \frac{M_k}{M_\pi} \frac{r_k}{r_k + 1} + \frac{M_x}{M_\pi} \frac{r_x}{r_x + 1}}{\frac{1}{r_\pi + 1} + \frac{M_k}{M_\pi} \frac{1}{r_k + 1} + \frac{M_x}{M_\pi} \frac{1}{r_x + 1}}$$

where r_i is the charge ratio of muons produced by the i -th process alone ($i = p, k, X$ for pion, kaon, and X-process muon production), and $M_i(E, \theta)dE d\theta$ is the number of muons produced from the i -th process in the energy interval $dE d\theta$. The curves plotted represent the prediction of a simple model in which the values r_i were assumed constant over the region of interest: $r_k = \alpha$, $r_x = 1.0$, and r_π as tabulated.

$$\frac{M_k(E, \theta)}{M_\pi(E, \theta)} = 1.875 \left(\frac{K}{\pi} \right) \frac{90 \text{ GeV} + E \cos \theta}{366 \text{ GeV} + E \cos \theta}$$

where the kaon/pion ratio K/π is taken as constant as tabulated. And assuming the direct process of muon production follows the same power law ($y = 2.7$) as kaons and pions,

$$\frac{M_x(E)}{M_\pi(E, \theta)} = \frac{R(90 \text{ GeV} + E \cos \theta)}{90(0.76)^{1.7} \text{ GeV}}$$

where R is the production ratio of X -process muons to pions. The value of this ratio was taken as $R = 0.02$ (the conclusion Of MASON [8]) and $R = 0$ (the usual picture).

Several conclusions can be drawn from a study of Fig. 2:

1. The data confirm the conclusion Of MACKEOWN and WOLFENDALE [9] that the charge ratio is too high to be accounted for by pionization alone.

2. A large K/π ratio (> 0.15) is unlikely if r_k is assumed to be large (e.g. if the production of K^+ is dominant as in the PAL and PETERS [10] conception of isobar decay: $N^* \rightarrow Y + K$).

3. The assumption that muons are produced from kaons and pions which come from isobars with constant relative production rates in this energy region is nearly untenable since this would mean a curve such as (a) in Fig. 2. The best fit to the data would then be with $K/\pi = 0$ (or $r_k = 1$ if one assumes kaon pair production which is unlikely from the Utah angular distribution result), which gives a straight line such as (b) in Fig. 2, in poor agreement with the higher energy data.

4. A better fit to the data than curve (b) can be achieved by either invoking the X -process or a decreasing r_p . In the latter case, if pion production is a result of isobar decay, the population of a set of isobaric states must be changing, or some sort of pionization process is emerging.

5. One may retain the assumption of isobars with constant relative production rates by assuming the charge ratio component from the X -process is unity (curve (d)). The fit could be enhanced by choosing a larger value for R , the parameter of the X -process.

References

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