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# LATERAL DISTRIBUTION OF MUONS UNDERGROUND*

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The radial extent of muon showers underground has been studied by measuring the separations between 3383 pairs of muons observed. The results are presented in the form of a decoherence curve which is compared to the theoretical predictions of ADCOCK, WDOWCZYK, and WOLFENDALE. This comparison indicates that the mean transverse momentum of these shower muons is between 0.6 and 1.0 GeV/c.

## Introduction

A feature of most models for hadronic high-energy interactions is the near constancy of the transverse momentum with a maximum in the vicinity of 0.4 GeV/c. There have been hints from time to time, mostly from air shower experiments, of a process with much higher transverse momentum: but these effects have not as yet been well established or universally accepted. Underground muon showers, which are a common feature of observations with the Utah detector, provide a unique opportunity to examine the transverse momentum distribution of secondary particles produced by interactions of cosmic ray primaries at the highest energies. In this paper, we describe the results of a study made during the first six months of running with the completed Utah detector.

## Data gathering

The University of Utah detector, located in a mine under the rugged Wasatch mountains, has been described previously in a series of three papers [1-3] and elsewhere in the proceedings of this Conference [4], so only the aspects of the detector which are pertinent to the present work and which are not mentioned in these references will be discussed here. The nearly parallel trajectories of muons comprising the underground muon showers are detected in digital spark counters triggered by water Cerenkov counters. Muons separated by as much as 12 metres may be studied in the main detector. Three outrigger detectors using similar spark counters located

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in an adjacent tunnel make it possible to study muons in these detectors coincident with muons in the main detector which have separations as great as 65 metres.

A pattern recognition computer program has been developed so that all but a fraction of a percent of the main detector events recorded on magnetic tape may be reconstructed and analyzed by a high speed digital computer. All the recorded events where a muon in one of the outrigger detectors was coincident with a muon in the main detector were hand-plotted and examined individually. During the period from January to June, 1969, more than 5000 pairs of parallel penetrating muons incident at zenith angles ranging from 40 to 70 degrees and having traversed 1900 to 4500 hg/cm$^2$ of rock overburden were recorded and analyzed. Events having multiplicity of 3 or greater were analysed by including each component pair of muons.

## Analysis

The separation between each pair of muons was calculated, and a distribution of these separations in 1 metre bins was compiled in an array of 12 x 48 angular bins (2.5 degrees zenith by 5 degrees azimuth). Then the angular bins were correlated with the rock depth in hg/cm$^2$ that muons from those particular directions must traverse. The technique used to fold out the complex aperture and the triggering requirements of the Utah detector have been discussed previously by PORTER arid STENERSON [5]. Using this method, the counting rates for an equivalent pair of 1 m$^2$ detectors as a function of their separations in metres (decoherence curves having the absolute units of counts m$^{-4}$ sec$^{-1}$ sr$^{-1}$) were obtained in 2.5 zenith angle bins and 500 hg/cm$^2$ depth bins.

We observe from our data in the range of zenith angles between 40 and 60 degrees and depths between 1900 and 3400 hg/cm$^2$ where statistical uncertainties are small that two things are at least approximately true: 1. the angular dependence of the decoherence curves compiled for 10° x 500 hg/cm$^2$ zenith-depth bins is slight, if any, and 2. the attenuation with depth of pairs is close to that given by the depth-intensity curve for vertical single muons. Accordingly, we have used the depth-intensity of single muons to combine the data at different depths. In addition, we make the reasonable assumption that the separation *x* between a pair of muons observed is proportional to ( sec $\theta$ ) / $E_{ì}$ where $\theta$ is the zenith of the arrival and $E_{ì}$ is the minimum muon energy required to reach the detector. Although reasonable, the data do not unambiguously establish this scaling law for muon separations. In our experimental arrangement, larger values of $\theta$ mean generally larger values of $E_{ì}$ and the two effects tend to cancel out to a certain extent. For the present, we have assumed that the above scaling law does hold, and we have used it to combine pair separations.

The resulting decoherence curve comprising 3383 muon pairs incident in a range of zenith angles between 40 and 60 degrees and normalized to 2500 hg/cm$^2$is show in Fig.

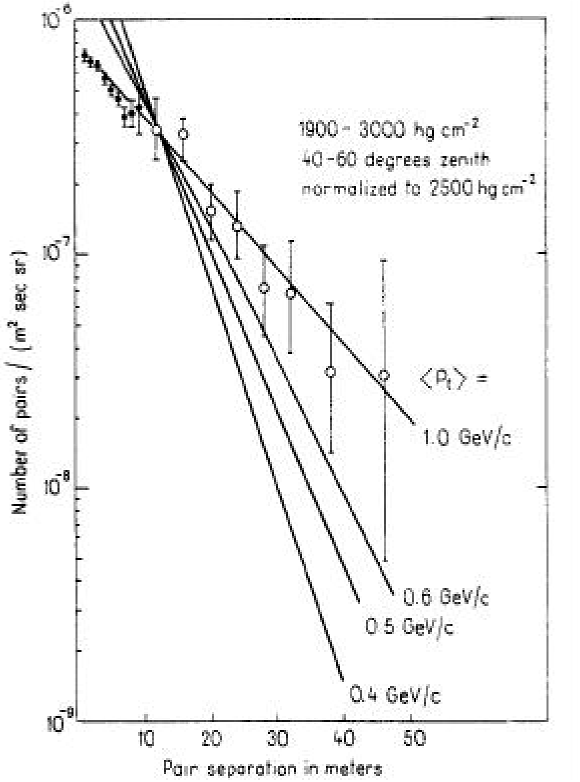


Fig. 1. Measured decoherence curve for 3383 pairs and comparison with the theoretical predictions of ADCOCK, WDOWCZYK, and WOLFENDALE

## Results

The results obtained must be considered preliminary for at least two reasons. First, more data is needed to establish the shape of the decoherence curves at the largest separations. Second, in the main detector, events which were too complex to be handled by the pattern recognition program must be hand-scanned. This work is not yet complete, but we anticipate that the addition of the hand-scanned data could increase the decoherence curves by as much as 20% for separations less than 10 metres. The theoretical decoherence curves plotted for mean transverse momenta running from 0.4 to 1.0 GeV/c are from ADCOCK, WDOWCZYK, and WOLFENDALE [6], and are the results of a detailed Monte Carlo calculation of shower development with the C.K.P. model for $\theta = 45°$ and $E_{ì} > 1000$ GeV. The normalization of these curves to our data point at 12 metres is ours, and was arbitrary. Comparing the data to the shape of the calculated curves indicates a mean transverse momentum between 0.6 and 1.0 GeV/c.

## References

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