Multiple muons in the Homestake underground detector

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(Received 5 November 1982)

The 113-m^2 water Cherenkov detector at a depth of 1480 m (4200 m water equivalent) in the Homestake Gold Mine, Lead, South Dakota, has been used to study multiple muons with $E_\mu \gtrsim 2.7$ TeV produced in cosmic-ray interactions by primaries of $10^{14}-10^{15}$ eV/nucleon. The decoherence curve and multiple-muon rates are presented.

I. INTRODUCTION

For many years, cosmic-ray data have suggested the existence of a high-transverse-momentum tail in the interactions of very-high-energy particles.[1] Cosmic-ray emulsion studies,[2–4] air-shower measurements of lateral distributions and multicore structure,[5,6] and underground muon observations[7] have indicated increases in multiplicities, cross sections, and average transverse momenta with increasing primary energy. These studies convey crucial data for theories of high-energy interactions based on the exceedingly successful notions of scaling and limiting fragmentation.[8] These results have been confirmed by the detailed data obtained at the CERN ISR,[9] Fermilab,[10,11] and the new CERN $\bar{p}p$ collider[12] at energies up to $\sqrt{s} = 540$ GeV. The interpretation of the results is complicated, however, by the fact that the primary-cosmic-ray composition is poorly known, and appears to be strongly energy-dependent near 10^{15} eV.[7,8,13]

In this paper we present the results of measurements of high-energy underground muons at a depth of 4200 m water equivalent (m.w.e.) in the Homestake Gold Mine, Lead, South Dakota. Underground muons, with energies in our case in excess of $E_{\mu,\min} \sim 2.7$ TeV, are unique among cosmic-ray components in that they carry direct information about the initial stages of the cascade generated by the interaction of the primary cosmic-ray particle high in the atmosphere. The separation distribution of muon pairs is presented in terms of a decoherence curve which can be interpreted to give an average transverse momentum $\langle p_t \rangle$ for pions produced in interactions of primary protons with $\sqrt{s} = 400 - 1000$ GeV. In Sec. II we describe the detector and the experimental procedure, and in Sec. III we present our results. A more detailed analysis of the decoherence curve and the rates of multiple muons is given in the accompanying paper,[14] which further discusses the implications of the results for high-energy interaction models and the cosmic-ray composition.

II. DETECTOR DESCRIPTION

The Homestake water Cherenkov detector[15,16] is located at a depth of 1480 m of rock in the Homestake Gold Mine. It consists (Fig. 1) of a water

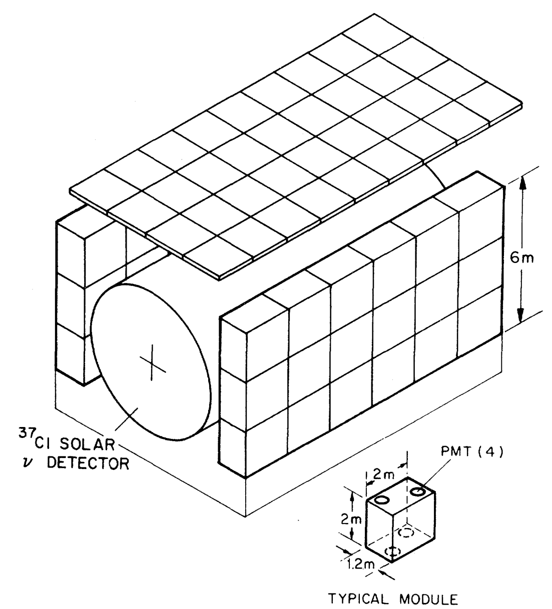

FIG. 1. Diagram of the Homestake water Cherenkov detector.

Cherenkov counter and liquid scintillation detector, with a horizontal surface area of 133 m^2, surrounding the ^{37}Cl Brookhaven solar-neutrino detector.[17] Thirty-six water Cherenkov detector modules are arranged on opposite sides of the detector room in two 6-m-high walls of optically isolated 2 m$\times$2 m$\times$ 1.2 m modules separated by 6.4 m between the two walls. The total active mass of these side Cherenkov detector modules is 150 tons of water. A top counter array consists of thirty-three 1.6 m$\times$1.6 m$\times$ 5 cm liquid scintillation counters. The bottom of the detector is a single large (150 ton) water Cherenkov counter. The walls of all detector elements are highly reflective. The water has been filtered, and 10 mg/1 of Amino G wavelength shifter added. Each side Cherenkov module is viewed by four 12.5 cm diameter hemispherical photomultiplier tubes operating under a fourfold coincidence requirement; the scintillators are viewed by two tubes per element; and a total of 48 tubes are used to view the bottom detector. Individual tube gains and thresholds are set by calibrating the detector in two ways. First, we periodically calibrate the individual detector modules with a ^{106}Rh source imbedded in a small plastic scintillator. The source emits 3.5-MeV β's, and the resulting scintillation light is seen in the detector photomultiplier tubes. Second, we obtain a continuous calibration by recording highly relativistic cosmic-ray muons passing vertically downward in a straight line through the detector. Such muons typically deposit 370 MeV in a single side Cherenkov module and can readily be identified on the basis both of their trajectory and pulse height. The detector is triggered by each event in which four photomultiplier tubes in a single Cherenkov module fire within a 200-nsec coincidence window. For each event, the pattern of photomultiplier-tube pulse heights and event arrival times is recorded on magnetic tape. The data are used to search for nucleon-decay events,[15] neutrino bursts,[16] and cosmic-ray muons. Nucleon decays are characterized by a large Cherenkov pulse from the initial decay, followed by a delayed pulse 2.2 μsec later from the decay of a stopping muon produced either directly or indirectly in the initial nucleon decay. Neutrino bursts are characterized by bursts of single low-energy events ($E_\nu \gtrsim 10$ MeV) arriving in a time interval of less than a few seconds. Muons transversing the detector are recognized by observing their multimodule tracks.

For the present analysis we restrict ourselves to nearly vertical muons. These are events in which three Cherenkov modules fire along a vertical trajectory—i.e., events with zenith angles $\theta < 18°$. In order to avoid confusion due to the finite dimensions of the detector modules, and to eliminate events due to local muon interactions in the surrounding rock, we identify events as due to simultaneous multiple muons only when they are separated by at least one full module width—i.e., we set a minimum separation of 2 m. The detector triggers on a vertical muon in a set of three Cherenkov modules, and records accompanying muons in other Cherenkov modules, the scintillators, and the bottom Cherenkov detector.

The detector is well suited to muon measurements by virtue of its depth and size. Based on a muon energy-loss rate $dE/dx = a + bE$, with $a = -2.5$ MeV cm^2/g and $b = -4\times10^{-6}$ cm^2/g, the depth corresponds to 50% penetration at a muon energy of 2.7 TeV. In addition, the detector is sufficiently large to detect muon pairs resulting from interactions with p_t as large as 2 GeV/c, where $p_t = E_{\pi,\min} d/h$, corresponding to a minimum pion energy

$$E_{\pi,\min} = (m_\pi / m_\mu) E_{\mu,\min} = 3.6 \text{ TeV},$$

detector dimensions typically $d \sim 10$ m, and an interaction height typically $h \sim 19$ km.

III. RESULTS AND DISCUSSION

In 18 months of running during 1979–1981 (398 effective days on), we observed a total of 7124 vertical muon events (see Table I). The overall single-muon rate is 2×10^{-4} sec^{-1}. Calculations of the detector's geometry factor for single vertical muons give 4.0 m^2 sr, resulting in a measured vertical single-muon flux of $(4.91\pm0.06)\times10^{-9}$ cm^{-2} sec^{-1}sr^{-1}, in good agreement with the Kolar measurement, as discussed in Ref. 18.

If $N(r)$ is the observed number of underground muon pairs with separation r, and dN/dr is the number of such events/m of separation in an observation time t, solid angle Ω, and total detector area A, then the separation distribution can be expressed in terms of the decoherence curve

$$R(r) = \frac{1}{2\pi r \epsilon(r) A \Omega t} \frac{dN}{dr}, \qquad (1)$$

where $\epsilon(r)$ is the geometric efficiency with which a muon pair can be detected at a given separation r. The 275 twofold events can be used to generate a

TABLE I. Rate of multiple muons.

Multiplicity	Number of events
1	6814
2	275
3	31
4	4
>4	0

TABLE II. Separation distribution.

r (m)	$\epsilon(r)$	$N(r)$	R ($m^{-4}sec^{-1}sr^{-1}$)
5.3±0.8	0.33	73	$(29.3\pm0.4)\times10^{-9}$
6.9±0.8	0.29	50	$(18.6\pm2.7)\times10^{-9}$
8.4±0.8	0.22	43	$(16.0\pm2.6)\times10^{-9}$
9.9±0.8	0.10	13	$(8.1\pm2.5)\times10^{-9}$
11.4±0.8	0.047	4	$(8.0\pm3.4)\times10^{-9}$
13.0±0.8	0.018	4	$(9.4\pm5.5)\times10^{-9}$

decoherence curve. These events are shown in Table II as a function of separation distance. The time-averaged efficiency $\epsilon(r)$ is determined from Monte Carlo simulations taking into account the detailed triggering requirements and geometry of the instrument and the efficiency and on-time of individual detector elements, and assuming vertical muon incidence. $N(r)$ is the number of events with separation in a 1.5-m-wide window about r; $dN/dr = N/1.5$ is the number of events/meter; and $R(r)$ is the measured decoherence curve calculated from Eq. (1) and shown as the solid points in Fig. 2.

Also shown in Fig. 2 are the earlier Utah results[7] at 4000 and 4800 m.w.e. Since the Utah measurements were made at a zenith angle of 62.5°, they typically resulted from primary-cosmic-ray interactions occurring at altitudes higher than at Homestake by a factor of 1.3. In order to correct for the higher altitude and longer path length, we therefore

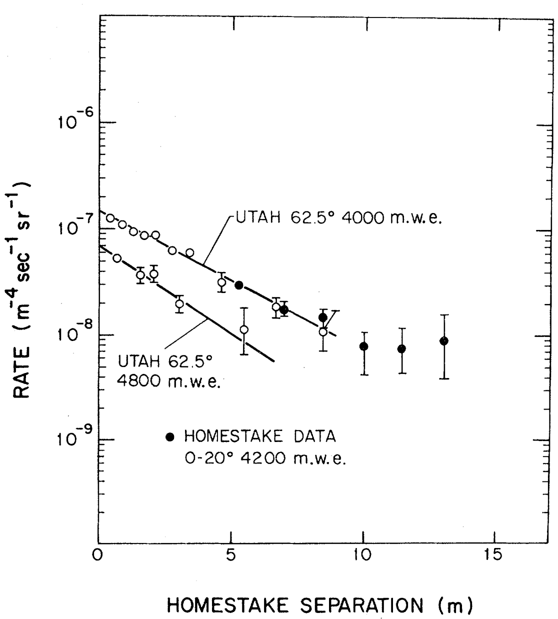

FIG. 2. Decoherence curve. The solid points are the present Homestake results; the open circles are the Utah results (Ref. 7) normalized to Homestake. The solid lines are of the form R_0e^{-x/x_0} using the best-fit parameters of Lowe, Bergeson, and Larson (Ref. 7).

compress the Utah separations by a factor of 1.3 sec (62.5°)=2.8. In the region of overlap (Homestake separations of 5—10 m), there is good agreement between the Utah and Homestake data. The Homestake experiment yields a somewhat flatter decoherence curve, however.

Full interpretation of the results requires a detailed Monte Carlo calculation simulating the full shower development and the precise detector response. Such a calculation has been performed,[14] taking into account various models of the cosmic-ray spectrum and composition. With a hadronic-interaction model assuming cross sections which increase with energy, and distributions of Feynman x and p_t which are energy-independent, Elbert *et al.*[14] have analyzed both the Utah and the Homestake results, and find that our data are consistent with $\langle p_t \rangle = 500$ MeV/c. This result does not depend on whether they assume a proton-rich or an iron-rich primary cosmic-ray composition.

The results of numerous accelerator[9,10,12] and cosmic-ray experiments[1–7] indicate a slow increase of $\langle p_t \rangle$ with $\sqrt{s}$, as shown in Table III. In particular, the Utah results, based on Monte Carlo calculations assuming a mixture of protons and iron in the primary beam, give $\langle p_t \rangle$ ranging from 500 to 670 MeV/c, depending on the details of their models. The CERN $\bar{p}p$ results[12] at $\sqrt{s} = 540$ GeV give $\langle p_t \rangle$ = 500 MeV/c. Our value is consistent with the CERN results.

The primary energy range of the present experiment is not a measured quantity, and can be determined only with the detailed Monte Carlo shower studies of Ref. 14. The typical energy of primaries producing the observed underground muons is 100—200 TeV/nucleon, corresponding to center-of-mass energies of 400—600 GeV. We are presently planning to install an air shower array on the surface above the underground detector in order to provide this measurement directly.[19]

TABLE III. Summary of $\langle p_t \rangle$ for recent high-energy experiments.

$\sqrt{s}$ (GeV)	$\langle p_t \rangle$ (MeV/c)	Reference
14	325±2	Fermilab (Ref. 11)
20	340	Fermilab (Ref. 10)
53	350	ISR (Ref. 9)
180	400±20	Balloon (Ref. 4)
200	440±20	Balloon (Ref. 2)
170—400	500—670	Utah underground muons (Ref. 7)
200—400	570	Air showers (Ref. 6)
200—1200	140—500	Chacaltaya (Ref. 3)
540	500	CERN collider (Ref. 12)
400—600	500	Present experiment

ACKNOWLEDGMENTS

We are extremely grateful to Mr. A. Gilles and the staff and management of the Homestake Mining Company for the invaluable assistance and cooperation they have provided us. We have benefited from numerous discussions with T. Gaisser, T. Stanev, and J. Elbert. This work has been supported by U.S. National Science Foundation Grant No. AST-79-08670 and U.S. Department of Energy Contract No. DE-AC02-81-ER-40012.

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