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Multiple Muons in MACRO

MACRO Collaboration (1)
presented by
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We show how an analysis of the multiple muon events in the Monopole Astrophysics and Cosmic Ray Observatory detector can be used to determine the cosmic ray composition. Particular emphasis is placed on the interesting primary cosmic ray energy region above 2000 TeV/nucleus.

An extensive study of muon production in cosmic ray showers has been done by Gaisser and Stanov (2). Results were used to parameterize the characteristics of muon penetration into the earth to the location of a detector.

The mean number of muons at a slant depth X is

$$\langle N_\mu \rangle = \frac{1}{E_\mu}(.0142)\left(\frac{E_p}{E_\mu}\right)^{.775}\left(1 - \frac{E_\mu}{E_p}\right)^{5.96}\sec\theta,$$

where E_p is the primary energy per nucleon, θ is the primary direction relative to the vertical, and

$$E_\mu(\text{TeV}) = .53(e^{.4X}-1)$$

is an effective muon threshold energy (so that $E_p > E_\mu$ is required). Each nucleon in a primary nucleus contributes this same average number of muons. The N_μ distribution is taken to be Poisson.

The lateral distribution of muons at the detector depth is

$$\frac{dN_\mu}{dR_\mu} \propto R_\mu e^{-2R_\mu/\langle R_\mu \rangle}, \text{ where}$$

$$\langle R_\mu \rangle = 3.13E_\mu^{-.46} + 13.2E_\mu^{-.31}\left(\frac{E_\mu}{E_p}\right)^{.62} .$$

Here R_μ is measured perpendicular to the shower core. The R_μ and N_μ distributions are uncorrelated.

These parameterizations yield predictions for the Kolar Gold Field experiment (3) which agree well with the data (4).

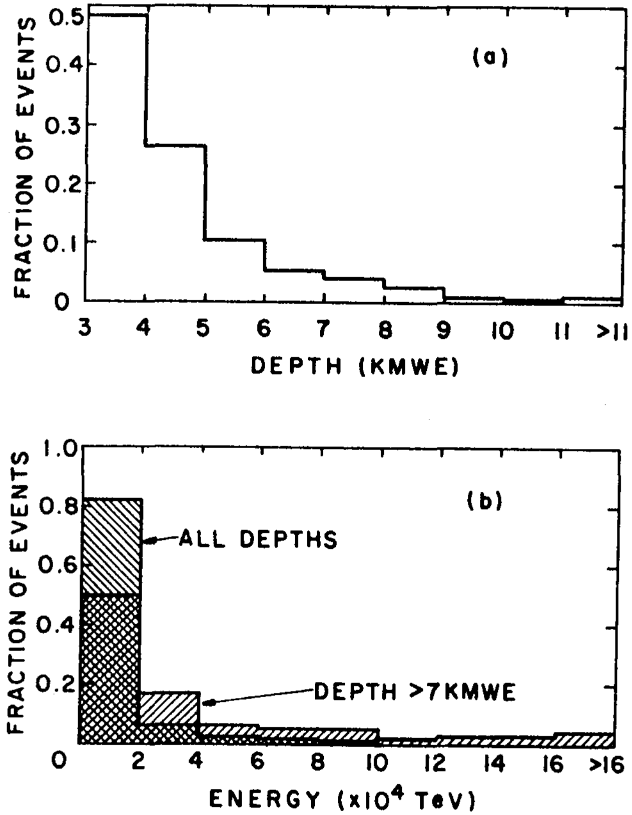

Fig. 1 a) Distribution of overburden (depth) that muons must penetrate to reach the detector. b) Distribution of primary cosmic ray energies (per nucleus) for all depths and for depths greater than 7 KMWE.

The MACRO detector is taken to be a horizontal rectangle 12m by 112m, and all muons striking this rectangle are assumed to be detected. (We are currently redesigning the apparatus so that it will have a significant size in the vertical direction; the present height is 5.7 m high).

Muons that reach the detector pass through a variable slant depth of material in the irregularly-shaped Gran Sasso Mountain. In Fig. 1a we show the slant depth distribution in units of KMWE. Because we measure muon directions with high resolution (~.2°), we can select on the slant depth and thereby have a data sample with a distribution of primary energies that can be changed. For example, in Fig. 1b we show the distribution of primary energies (per nucleus) for all depths, and separately for depths that are greater than 7 KMWE. The percentage of events with primaries < 2000 TeV/nucleus is 31% for all events but only 8% for the restricted sample.

A major goal of MACRO is to determine the cosmic ray composition above the 2000 TeV "knee" in the energy distributions. We have studied four models for this high energy composition:

1.	Fe	All primaries are iron nuclei.
2.	Md	A mix of primaries is used with iron dominating at high energy.
3.	LE	Primary composition at high energies is the same as at 50 GeV/nucleon.
4.	p	All primaries are protons.

Models Md and LE are described in reference 3.

In Fig. 2 we show the detected muon multiplicity distributions for the four models (solid curves), all normalized to the single muon rate.

For a given nucleus energy, the proton has a much larger energy per nucleon than iron, so protons give many more single muon events; however, the iron nucleus produces many more muons so its multiple muon to single muon ratio is larger. However, lateral spreads (decoherence) from iron are larger, so a large detector like MACRO is needed to exploit this difference.

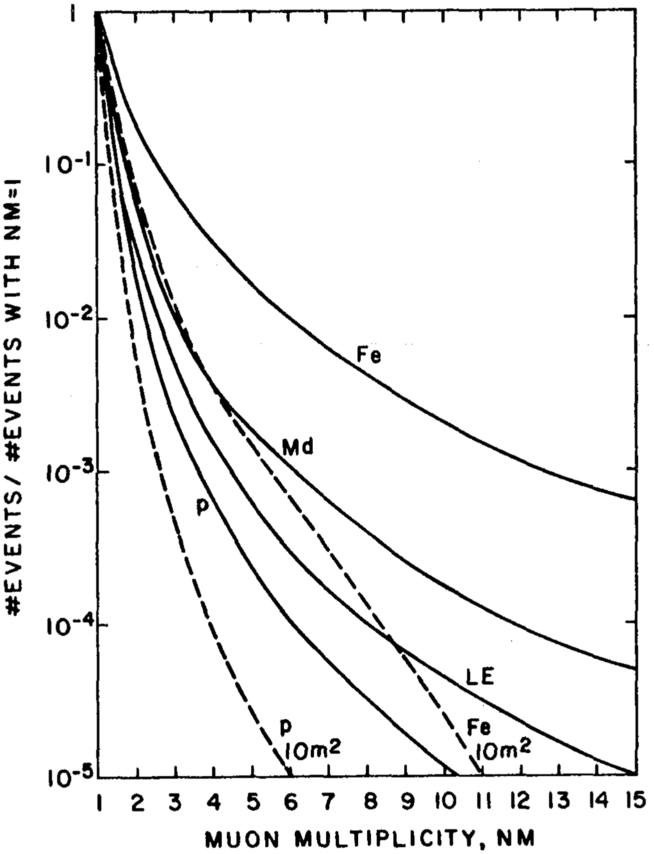

Fig. 2 Muon multiplicity distribution divided by single muon rate for various hypotheses. (See text.)

The dashed curves in Fig. 2 show how difficult it is for a small detector ($10m^2$ area) to measure high multiplicities. For 10 μ's, the Fe hypothesis yield is down two orders of magnitude. The absolute MACRO yields are about 500K/year for Fe and 13M/year for protons, including single muon events. Depending on composition, the number of events with NM > 5 will be 500 to 20,000!

One aspect of the muon decoherence which is particularly sensitive to primary composition is the maximum separation of a pair of muons in a multiple muon event. In Fig. 3 we show this distribution for the four composition hypotheses and for three different ranges of slant depth (and thus three different primary energy distributions).

Figures 2 and 3 both show that MACRO is sensitive to the cosmic ray primary composition at high energy.

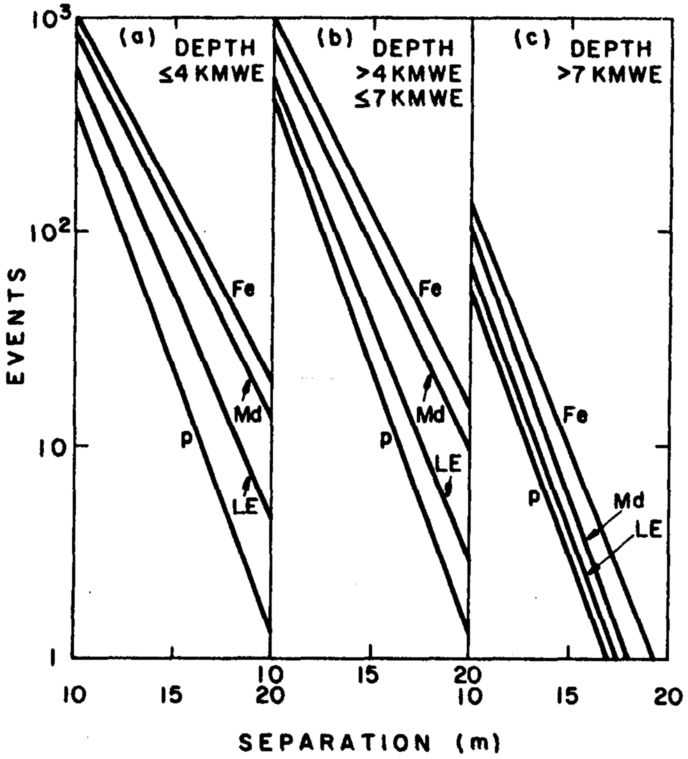

Fig. 3 Distribution of maximum two-muon separation in a multiple muon event for three ranges of overburden.

References

1. B. Barish, these proceedings.
2. T. Gaisser and T. Stanev, to be published in Nuclear Instruments and Methods.
3. G.B. Yodh, Todor Stanev and T.K. Gaisser, in Proceedings of ICOBAN 1984.
4. G. Yodh, T. Stanev, and T. Gaisser, 1984 ICOBAN, Park City, Utah.