The influence of high energy muon transverse separation on determination of primary cosmic ray composition

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Abstract

Measurements of EAS using a wide angle Cherenkov light detector in coincidence with the Soudan 2 underground muon detector are sensitive to cosmic ray primary composition. A comparison of the observed muon multiplicity distribution with that derived from simulated EAS shows that no realistic combination of primary masses leads to the measured distribution. It is believed that this is due to the inability of the simulations to accurately represent the transverse separation of high energy muons.

1 Introduction

The first air Cherenkov array located at Soudan was a single wide angle Cherenkov light array composed of five detectors, each with four PMTs (Mualem, et al., 1997).It operated in coincidence with the Soudan 2 detector (Allison, et al., 1996) during the winter months, October, 1994 through April, 1997. The Soudan 2 detector is situated 700 m underground and enables muon trajectories to be determined with a precision of $0.5°$; muons are detected within a volume 12 m $\times$ 24 m $\times$ 8 m high. After applying stringent criteria, 199 coincident cosmic ray events were selected for further analysis, from a total live time of 195 hours. Primary energies were determined to $\sim$ 20% using the amount of light detected by the Cherenkov detector in conjunction with the direction and core position of the events determined from the Soudan 2 detector. Reconstructed energies ranged from $100\ TeV - 20\ PeV$. The overall flux determined from these data was relatively insensitive to the assumed primary mass and was consistent with previous measurements.

2 Muon multiplicity distributions

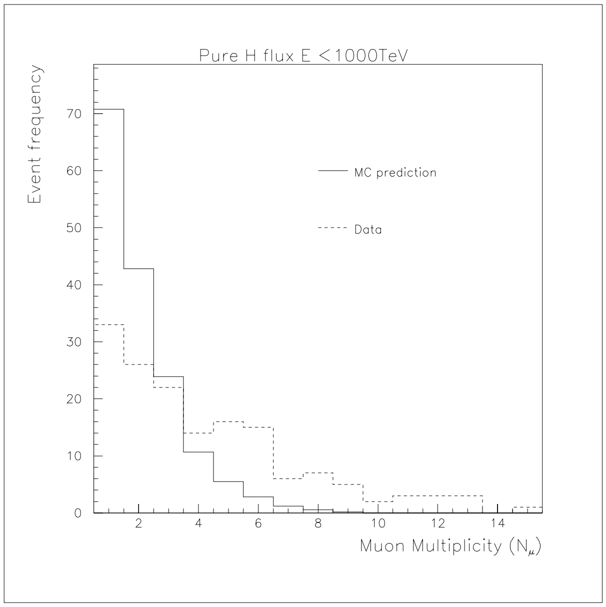
In principle, the elemental composition of the primary cosmic ray flux can be determined by comparing observed muon multiplicity distributions with those expected from simulations as a function of primary energy and mass. We have used the SIBYLL (Fletcher, et al., 1994) interaction model for this purpose.

Due to the limited number of events in our data, we consider two energy regions: a high energy region above $1000\ TeV$ (i.e., above the *knee*, approximately), and a low energy region below $1000\ TeV$ extending down to $\sim\ 100\ TeV$. In Figure 1 we compare the observed underground muon multiplicities with those predicted for pure hydrogen and pure iron primary flux compositions.

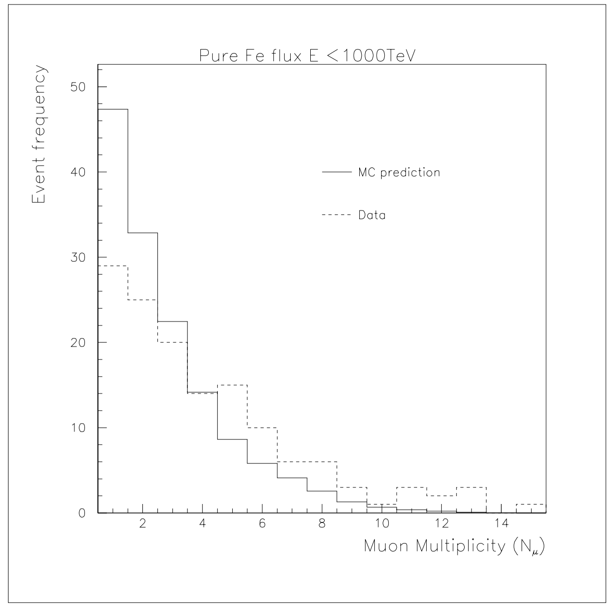
As expected, the Monte-Carlo predictions for iron primaries are skewed to higher muon multiplicities than for hydrogen, since the average number of underground muons is higher for iron primaries above a few hundred TeV. However, the data distributions are skewed to even higher muon multiplicities than expected for iron primaries. The effect is present for both energy regions, although it is less strong at higher energies. Based on these comparisons, we conclude that the best agreement between data and simulations is obtained with high mass primaries, but that the average mass must be substantially greater than that of iron. Direct measurements in the lower energy region (Watson, 1997) have shown that this is unlikely.

3 Influence of transverse momentum

Several possible explanations for this discrepancy have been investigated, both in the data and in the simulations. These include: muon propagation and counting, primary energy determination, simulated muon yields and transverse momenta, and hadronic interaction models. The only factor strong enough to bring the data and simulations into agreement is the simulated muon transverse momentum distribution.



(a)



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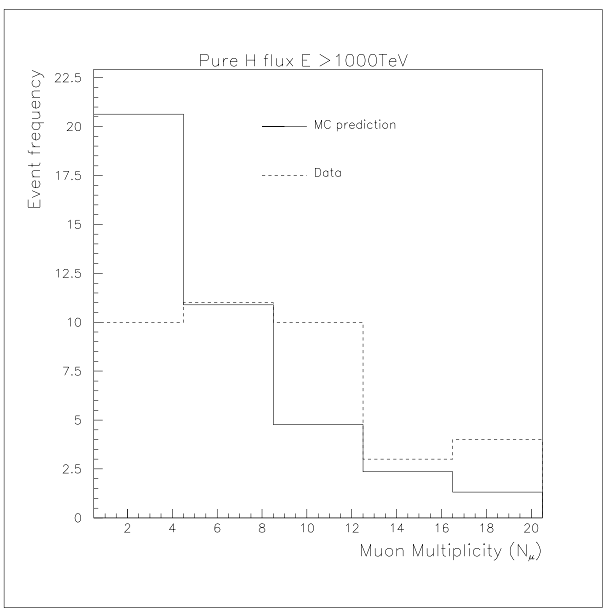

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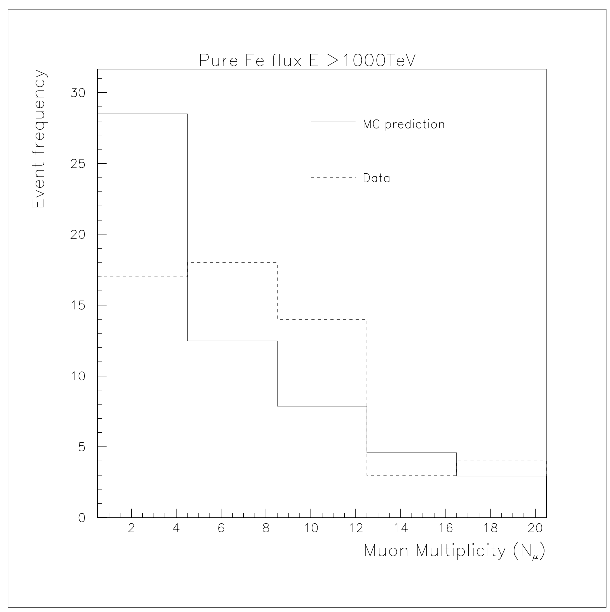

(d)

Figure 1: Event frequency distribution for four cases: pure hydrogen flux at low energy, pure iron flux at low energy, pure hydrogen flux at high energy, and pure iron flux at high energy.

To show the influence of a change in the assumed transverse momentum distribution, the simulation was run for a typical event with a zenith angle of $24°$, azimuthal angle of $156°$, and an energy of $5PeV$. The predicted muon multiplicity distributions were then calculated for three different muon lateral displacements: unaltered, doubled, and halved. The results are shown in Figure 2, along with the muon multiplicity distribution of the data for comparison. The influence of rescaling on the multiplicity distribution for the hydrogen primary is very strong. As expected, doubling the separations causes a strong skewing of the expected multiplicity distribution to small muon multiplicities, while halving the separations causes a strong skewing to high multiplicities. Rescaling the muon separations for iron primary events shows a similar influence on the muon multiplicity distribution. It is interesting to note that the effect is stronger for hydrogen primaries than iron primaries. This may be a reflection of the ~ 56 times lower energy of the nucleon in an iron-nucleus collision; the effect was also found in a comparison by Knapp et al. (Knapp, et al., 1996)

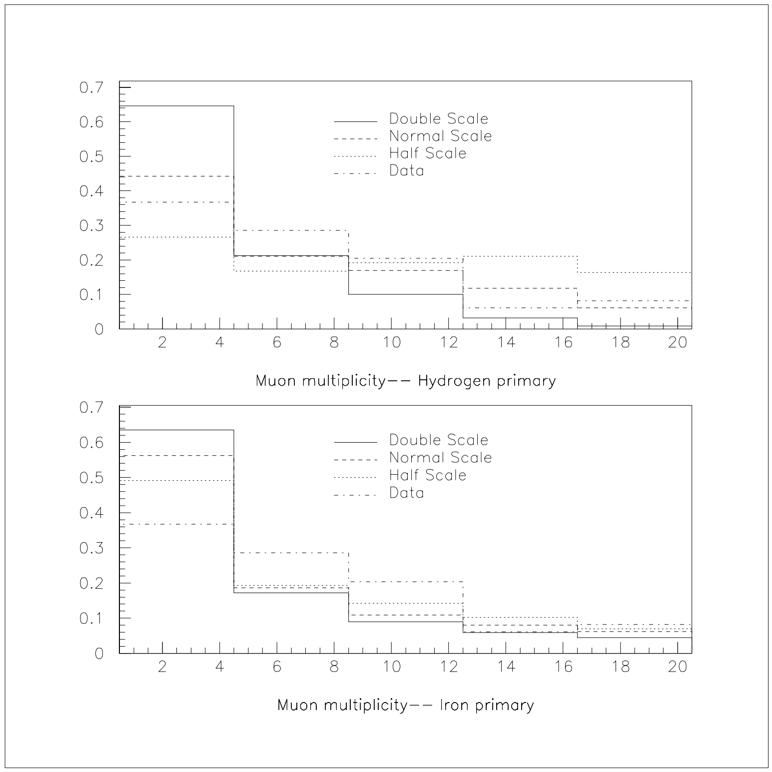

Figure 2: Influence of muon lateral displacement rescaling on the multiplicity distribution for hydrogen and iron primaries.

We conclude that, in order to fit our data with a realistic elemental composition of the primary cosmic rays in this energy region, the simulated transverse momentum distribution of the high energy muons must be considerably narrowed.

4 Hadronic interaction models

The details of the hadronic interactions are very important for the high energy muons observed deep underground. These $\sim$ TeV muons are produced very early in the cascade, typically after only 3 hadronic interactions. The typical angular spread of muons is $\sim 20\ m/20\ km$ (a typical lateral separation divided by the production height). In this small angular region with small transverse momentum and high energy, essentially no direct information exists. The simulations must rely on long extrapolations, or use theoretical predictions.

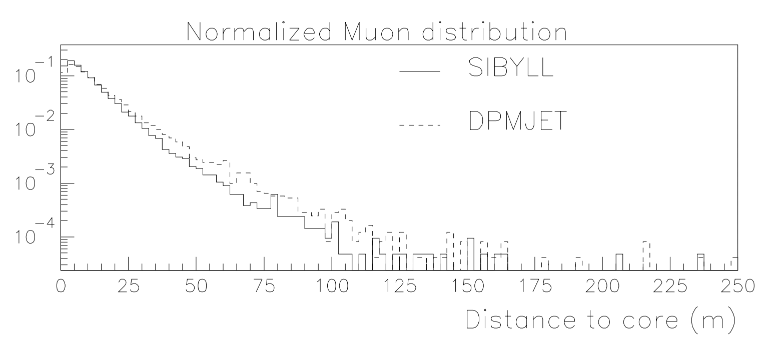

Figure 3: Influence of hadronic interaction model on the muon distribution for hydrogen primaries.

The particular hadronic interaction code used in most of our simulations was a hybrid code consisting of NUCLIB, which is responsible for determining the interaction points of the nucleons from incident nuclei other than hydrogen. Individual nucleon interactions are treated with SIBYLL. Daughter particles are tracked until their energies fall to pre-set thresholds.

Interaction model	$R_{avg}(m)$	$R_{rms}(m)$
SIBYLL	10.85	11.36
VENUS	10.76	11.49
QGSJET	11.85	13.16
HDPM	12.76	15.99
DPMJET	13.19	13.94

Table 1: Average and RMS deviation of muons from the core for various interaction models.

To further investigate the influence of the particular hadronic interaction model, we simulated 1000 1 PeV proton initiated showers using the CORSIKA 5.62 simulation program (Heck, et al., 1998). This allowed direct comparison of the muon distributions predicted by five different interaction models: SIBYLL, VENUS(Werner, 1993), QGSJET(Kalmykov, et al., 1994), HDPM(Capdevielle, 1989), and DPMJETII(Battistoni, et al., 1995) to determine if any one predicts a sufficiently narrow distribution to fit our data. The overall results are summarized in Table 1, with representative distributions from two of the most disparate models plotted in Figure 3. Only one interaction model, VENUS, predicts a mean muon separation that is less than that of SIBYLL. Since it was shown in the previous section that the predicted muon separation needs to be *significantly* reduced to match the data, we conclude that none of the tested models could lead to consistency with our data for any realistic cosmic ray composition. While the models tested are not a complete set of all possible models, they represent a significant sample of the available models, approaches and theories.

5 Conclusions

Deep underground muon detectors are sensitive to the primary cosmic ray composition when used in conjunction with other accurate calorimetric techniques, such as atmospheric Cherenkov light. However, the current state of experimental data and interaction theories describing the transverse momentum at high energy and small angles is inadequate to provide the required definitive simulations.

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