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Ultra High Energy Cosmic Ray Composition from Surface Air Shower and Underground Muon Measurements at Soudan 2*

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Abstract

The Soudan 2 experiment has performed time-coincident cosmic ray air shower and underground muon measurements. Comparisons to Monte Carlo predictions show that such measurements can make statistically significant tests of the primary composition in the "knee" region of the cosmic ray spectrum. The results show little evidence for an increase in average primary mass with energy up to $\sim 10^4$ TeV per nucleus. Some systematic uncertainties remain, however, particularly in the Monte Carlo modelling of the cosmic ray shower.

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1 Introduction

One of the outstanding problems in cosmic ray physics is understanding the ***knee***, the steepening of the primary spectrum between 10^3 and 10^4 TeV per nucleus. An understanding of the isotopic composition in this region may shed light in the origin and acceleration of cosmic rays. Simple ***leaky box*** acceleration models, for example, predict an increase in average mass near the knee as light, magnetically rigid nuclei begin to escape the galactic magnetic field, leaving heavier, less rigid nuclei behind. Other models propose new sources of light nuclei near the knee such as supernova remnants or active galactic nuclei, which produce constant or even decreasing average mass vs. energy functions through the knee region. The Soudan 2 experiment tests these theories by comparing Monte Carlo predictions for various composition models to coincident observations of surface shower size and deep underground muon multiplicity. This analysis appears to have statistical significance in the region of interest.

The Soudan 2 nucleon decay detector [1] is a large modular drift calorimeter located in the Soudan Underground Mine State Park. The minimum overburden is 2090 mwe, corresponding to muon threshold energy $\simeq 0.8$ TeV. The detector was under construction while taking the data described here, with mass increasing from 688 to 894 metric tons and horizontal area from 93 to 121 m^2. Soudan 2 was completed in November 1993 with mass 963 tons and area 130 m^2. The Soudan 2 underground detector measures muon multiplicity and direction with ~ 1 cm spatial and $< 1°$ angular resolution.

The Soudan 2 surface air shower detector is located at elevation 490 m asl, 714 m above the underground detector, at local zenith $\theta = 13°$ and azimuth $\phi = 116°$. The surface detector consists of 480 proportional tubes, each 2.54×2.54 cm^2 and 6.7 m long, summed in 240 horizontally adjacent pairs. The tubes have no pulse height or longitudinal resolution; they merely serve to count the number of particles which hit the detector. The proportional tubes are two layers deep with total surface area 41 m^2.

Data are analyzed by comparison to Monte Carlo calculations based on previously proposed energy dependent composition models, described below. The surface shower size is calculated according to Gaisser [2], with fluctuations to match Gaisser *et al.* [3]. Shower density is calculated according to the modified NKG distribution [4], with fixed shower age $s = 1.25$ and Molière radius $r_1 = 79$ m. Nuclear superposition is employed throughout. The number and radial distribution of the underground muons are based on the parametrizations of Forti *et al.* [5].

Surface detector hit information is stored for 128 μs and read out when a trigger is received from the underground detector, signifying a possible underground muon event. The reconstructed shower size S_R, the estimate of the total number of particles in the shower at surface detector depth, is obtained from the surface particle density and shower core position determined from the underground muon tracks, by inserting them in the inverted NKG formula. While it is the underground muon multiplicity which provides a test of the primary composition, the surface shower size estimate makes this analysis more sensitive to energy dependent effects than is possible with underground measurements alone.

2 Data and Monte Carlo

The data presented here were collected over 6384 live hours from 2 July 1991 to 20 July 1993. Preliminary event selection required at least one underground muon track (minimum length 1 m) and at least two separate two layer hits in the surface detector. Event timing separates coincident events, in which the surface and underground detectors are struck by particles from the same cosmic ray shower, from background, in which separate showers strike the two detectors independently. Fig. 1 shows the distribution of surface detector hits (after all cuts, see below) relative to the expected coincident time. The 3 μs width of the in-time peak (from -1 to +1 μs) is consistent with the 1 μs surface detector timing resolution.

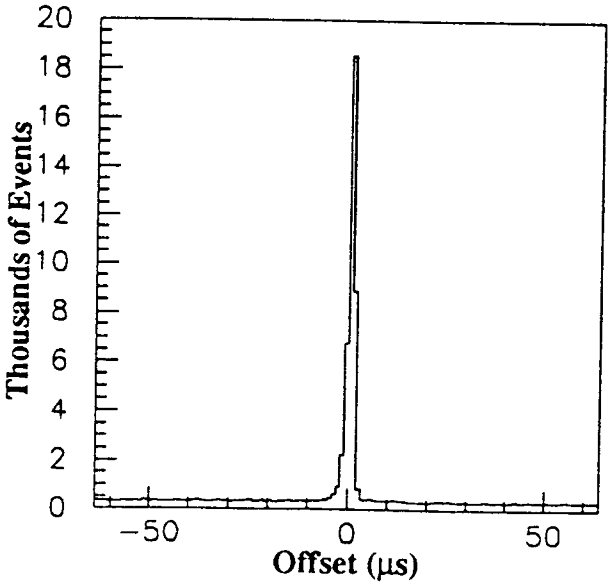


Figure 1: Timing histogram for events (after cuts) with two or more hits in the surface detector, relative to that expected for coincident events (offset=0).

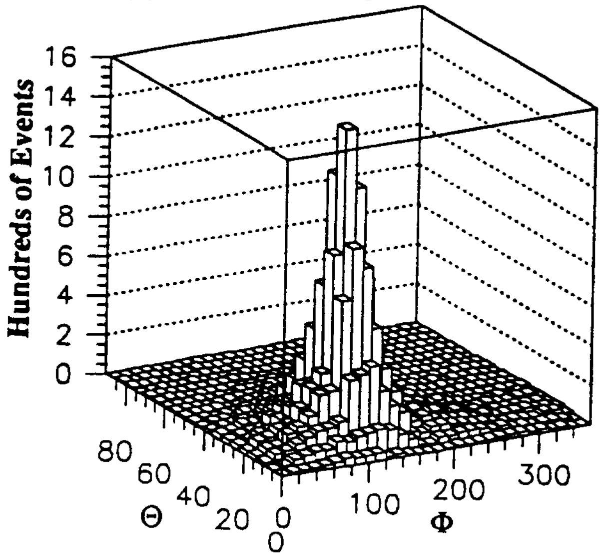
Fig. 2 shows that in-time events point toward the surveyed position of the surface detector while the out-of-time events exhibit the angular distribution characteristic of all underground muon events. This is consistent with a background consisting of real underground muons randomly associated with independent showers in the surface detector.

Three additional cuts are employed: (1) observed underground muon multiplicity is restricted to $N_\mu^{obs} \leq 7$, above which point the small number of events makes statistically accurate measurements of the software efficiency difficult; (2) surface detector multiplicity is restricted to $N_s \leq 20$ due to instrumental anomalies which we observed for extremely dense showers; and (3) the separation of the shower core from the surface detector is restricted to $r < 300$ m due to a disagreement between the number of high radius events predicted by the Monte Carlo and observed in the data. The last effect may reflect the inability of the relatively simple shower particle lateral distribution model used here to fit the data at large radii, and is described in earlier surface-underground studies at Soudan [6]. The cuts leave 34,222 in-time events including a background of 1031 ± 32. In this analysis the background is subtracted using the characteristics of the out-of-time events. The net coincident rate is 5.20 ± 0.03/hr, or 124.8 ± 0.7 per live day.

The data are compared to four realistic and three *ad hoc* composition models: the Forti *et al.* parametrizations of the Proton Poor (PP) [7], Maryland (MD) [8], Constant Mass (CMC) [9], and Linsley [10] compositions; and proton (H), helium (He), and iron (Fe) models using the Das Gupta all particle flux [6]. All four realistic models are dominated by light nuclei at low energy (below 100 TeV) to match direct observations. The PP and MD models predict compositions which rapidly become heavy above a few hundred TeV according to standard rigidity dependent containment models. The CMC model also predicts an increase in mass at high energy, but this increase is more gradual and does not occur until $E > 2000$ TeV. The Linsley model, on the other hand, predicts a *decrease* in average mass above 100 TeV due to the introduction of a new galactic source of light nuclei.

Above a few TeV/nucleon, heavy nuclei produce more muons at Soudan 2 depth than do light nuclei of the same total energy, making the underground muon multiplicity distribution sensitive to primary composition. In addition, the Soudan 2 surface detector can be used to estimate the energy of the primary cosmic ray, making this analysis more responsive to energy dependent effects. The relationship between energy and S_R, the number of shower particles at surface detector depth as determined from inverting the modified NKG formula, is determined from the Monte Carlo as shown in Table 1.

(a) In-Time Events



(b) Out-of-Time Events

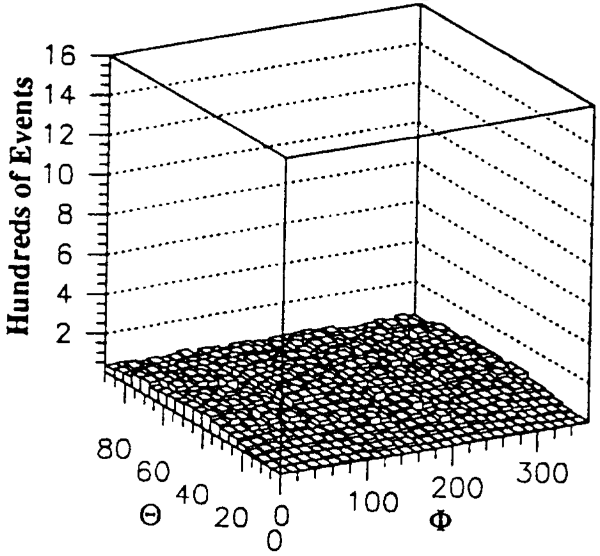


Figure 2: Local zenith (θ) and azimuthal (ϕ) angles of events with two or more hits in the surface detector. Those inside the coincident time window (a) tend to point near the surveyed surface detector position; events outside the coincident window (b) display the characteristic angular distribution of all underground muon events.

Table 1: Reconstructed Shower Size (S_R) and Total Primary Energy, from the Monte Carlo.

S_R	Median Primary Energy (TeV)		
	H	He	Fe
10^3	30	40	100
10^4	100	120	300
10^5	800	1000	2000
10^6	5000	6000	10,000

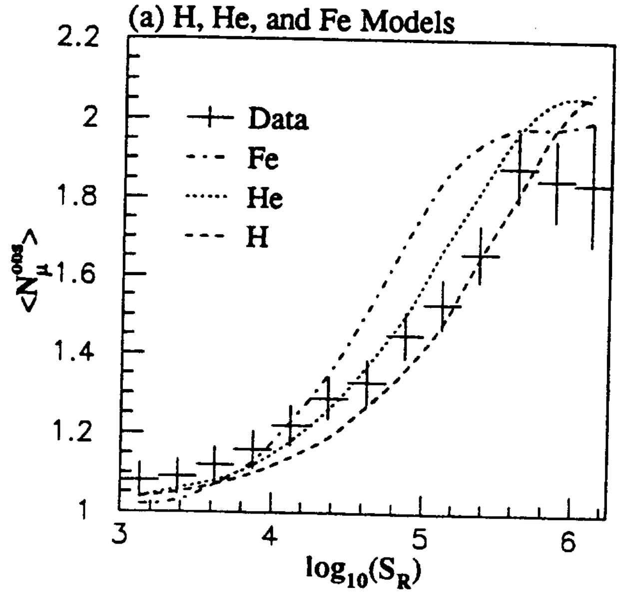
3 Systematics and Analysis

The underground muon multiplicity is the key observable for composition studies, and so systematic uncertainties in the total number of underground muons N_μ are of primary concern. There are two main contributions: the Monte Carlo muon production parametrization; and uncertainties in the depth and composition of, and muon transport through the Soudan 2 overburden. Comparisons of different parametrizations [5, 11] indicate a systematic uncertainty in $\langle N_\mu \rangle$ of up to 20% for the highest simulated shower sizes ($S_R \sim 10^6$). Effects due to uncertainties in the rock overburden and muon transport are calculated directly from the parametrization, and approach 14% at the highest simulated energies. These effects are less for heavier nuclei and approach zero as primary energy decreases to the threshold for producing muons at Soudan 2 depth, at which point all observed events are single muons regardless of the Monte Carlo. Furthermore, at increasing energy these effects remain much smaller than those due to the composition. (At the highest observed shower sizes iron nuclei produce a factor of five more underground muons than do protons.)

However the net systematic effect on the average *observed* underground muon multiplicity $\langle N_\mu^{obs} \rangle$ is not as large as the effect on the average *total* multiplicity $\langle N_\mu \rangle$ because the Soudan 2 detector generally does not observe all the muons in the shower. The $N_\mu^{obs} \leq 7$ restriction further limits the observed effect. The Monte Carlo indicates that the total effect on $\langle N_\mu^{obs} \rangle$ due to the systematic effects considered here varies from zero near threshold to 4% at reconstructed shower sizes $S_R \sim 10^5$, decreasing again at the highest observed shower sizes to approximately 2%. In order to be conservative we apply a uniform systematic uncertainty of 4% to the Monte Carlo predictions for $\langle N_\mu^{obs} \rangle$.

Although the composition analysis is based on underground muon multiplicity, uncertainties in the reconstructed shower size S_R are important as well because they determine the energy sensitivity of the experiment. First, there is a ±50% statistical effect due to the low average surface multiplicity, which is four. This is comparable to the fluctuations in size due to natural variations in shower development (point of first interaction, *etc.*), which range (for proton primaries) from a factor of two at 10^2 TeV to ±30% at 10^4 TeV. Second,there

(a) H, He, and Fe Models



(b) MD, PP, CMC, and Linsley Models

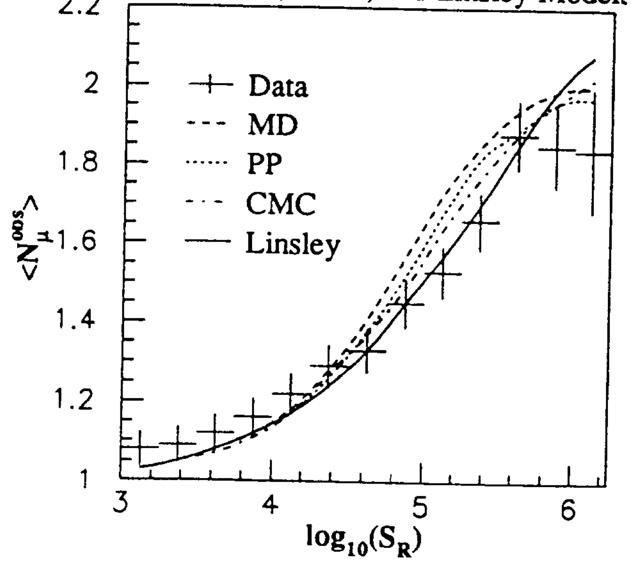


Figure 3: Average observed muon multiplicity $\langle N_\mu^{obs} \rangle$ as a function of $\log_{10}$ of the reconstructed shower size S_R. The systematic uncertainty of $\pm 33\%$ in S_R is equal to the bin width of ± 0.125 in $\log_{10}(S_R)$. The experimentally defined limit $N_\mu^{obs} \leq 7$ causes the Monte Carlo predictions to converge at high S_R.

may be systematic effects due to the use of fixed age s and Moliére radius r_1 [12]. These contributions are radially dependent, and are small ($< 20\%$) for radii less than 200 m, within which approximately 80% of the events discussed here fall. At the greatest allowed radii ($r = 300$ m), the effects may be as large as 30-35%. They increase dramatically at very large radii, corresponding to the region in which the data and Monte Carlo simulation no longer provide satisfactory agreement. While the systematic error in shower size reconstruction may be less at smaller radii, in order to be conservative a systematic uncertainty of ± 0.125 in $\log_{10}(S_R)$ ($\pm 33\%$ in S_R) is uniformly applied.

The essential results of the experiment are summarized in Fig. 3, which shows the observed and predicted values of $\langle N_\mu^{obs} \rangle$ as a function of $\log_{10}(S_R)$. Table 2 contains the χ^2 results.

The reconstructed shower size range of $S_R = 10^3$ to $S_R = 10^4$ corresponds to primary energies from 30 to 300 TeV, for which the multiplicity analysis does not distinguish among the models, except that it does not favor the Fe model which produces essentially no multiple muon events at these shower sizes because the energy per *nucleon* is too low. There may also be a systematic tendency for the Monte Carlo to underestimate $\langle N_\mu^{obs} \rangle$ in this range, but for the lighter models this is within the systematic error.

From $S_R = 10^4$ to $S_R = 10^5$, corresponding to proton primaries from 100 to 800 TeV, the realistic and He models appear to fit the data reasonably well, but the extremely light (H) and heavy (Fe) models do not. The fact that χ^2/DoF< 1.0 for some models may indicate that the systematic error has been overestimated, in which case the experimental evidence may also favor the lighter realistic models over their heavier counterparts. Without further study of the systematic issues (particularly those concerning the Monte Carlo), however, it is difficult to quantitatively evaluate such an hypothesis. For the lighter realistic models (CMC and Linsley) $\langle \ln A \rangle$ ranges from 1.2 to 1.7 in the region $S_R = 10^4 - 10^5$; for the heavier models $\langle \ln A \rangle$ ranges from 2.0 to 2.7.

From $S_R = 10^5$ to $S_R = 10^6$, corresponding to proton primaries from 800 to 5000 TeV, the best fits are Linsley and H, with $\langle \ln A \rangle$ from 0.0 to 1.2. In the same energy range $\langle \ln A \rangle = 1.7$ to 1.9 for the CMC model, and $\langle \ln A \rangle = 2.5$ to 3.1 for PP and MD. The predictions of all the models converge above $S_R = 10^6$, where the average muon multiplicity at Soudan 2 depth exceeds the experimental limit of $N_\mu^{obs} \leq 7$, regardless of primary nuclear species. Monte Carlo analysis shows that a future study of the $N_\mu^{obs} \geq 8$ events (once enough statistics have been obtained to completely understand the software efficiency at high multiplicity) should extend our composition sensitivity to the highest observed energies.

Table 2: χ^2/DoF ($N_{DoF} = 4$) for $\langle N_\mu^{obs} \rangle$ vs. $\log_{10}(S_R)$ (Fig. 3). The last entries are averages and thus have $N_{DoF} = 12$.

S_R	H	He	Fe	PP	MD	CMC	Lnsly
$10^3 - 10^4$	1.28	0.87	1.91	1.27	1.23	1.53	1.09
$10^4 - 10^5$	3.21	0.67	5.20	1.11	1.45	0.71	0.74
$10^5 - 10^6$	0.59	3.44	8.02	2.25	4.12	1.39	0.75
$10^3 - 10^6$	1.69	1.66	5.04	1.55	2.27	1.21	0.86

4 Conclusions

Simultaneous surface and underground cosmic ray measurements appear to have the potential to distinguish among cosmic ray composition models at energies from approximately 100 TeV to 5000 TeV, extending to the knee region of the primary spectrum. Furthermore, the results of this Soudan 2 surface-underground analysis, interpreted in terms of the Monte Carlo models described above, do not support any significant increase in average primary mass with energy in this range. This is in substantial agreement with previous measurements based on underground muon analysis alone, which have involved more detailed Monte Carlo models [13, 14]. Similar results from other combined surface-underground experiments have also been reported, in [6] based on a parametrized Monte Carlo and in [15] based on a more detailed code. The results presented here also generally agree with direct measurements below 100 TeV per nucleus. Above this point, however, JACEE data [16] indicate that the average mass may increase substantially, to $\langle \ln A \rangle = 2.33 \pm 0.27$ at 400 TeV, but this may be consistent with the Soudan 2 surface-underground results given the uncertainties in these experiments. Finally, the most recent Fly's Eye analysis [17] does appear to give a substantially different result, indicating that the composition changes from extremely heavy near 10^5 TeV per nucleus to extremely light near 10^7 TeV per nucleus, but the Fly's Eye findings concern energies more than an order of magnitude higher than those discussed here.

Further analysis efforts should be directed primarily toward three goals. First, the Monte Carlo systematics must be treated in detail, because even at this early stage in the analysis uncertainties are dominated by systematic rather than statistical considerations. Second, a better understanding of the surface particle radial distribution would allow the use of the events which land far from the surface array ($r > 300$ m), expanding the energy range of the experiment, in particular to the region overlapping with Fly's Eye measurements. Third and last, a better understanding of software reconstruction, possible through detailed study of the interaction and propagation of high energy muons inside the Soudan 2 detector, will allow our muon data to be extended to higher multiplicitites.

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