Towards a New Cosmic Ray Composition Measurement in the Knee Using a Dual Air Cherenkov Array

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Abstract

We present a new dual non-imaging Cherenkov array. The array, which is operated in coincidence with the Soudan 2 underground tracking calorimeter, was designed to make multi-parameter measurements of extensive air showers for the purpose of extracting the composition of the primary cosmic rays. Preliminary results from the initial seasons of operation will be presented at the conference.

1 Introduction

The "knee" artifact (E $\sim 10^{15}$ eV) in the cosmic ray energy spectrum still awaits an adequate explanation. It likely represents a cross-over from one set of source, propagation, and acceleration phenomena to another, but the details of this change are still disputed. Convincing and consistent composition measurements, which could help inform and constrain models, have yet to emerge for this region.

The lack of results around the knee can be largely explained by the fact that the knee coincides with the practical threshold that separates direct from indirect cosmic ray measurements. Beyond the knee, acceptance and live-time requirements exceed the practical capabilities of satellite and balloon-based instruments. Thus, indirect studies of extensive air shower properties must be performed, and cosmic ray properties inferred from their measurements.

The present investigation is an extension of the long-standing Cherenkov-based cosmic ray program at Soudan (Mualem, *et al.*, 1995). In the previous iteration, the experiment comprised a single detector station operated in coincidence with the underground calorimeter. Results from that detector are presented at this conference (Mualem, *et al.*, 1999). The recent addition of a second Cherenkov detector station has extended the capabilities of the Soudan program to include the ability to make measurements of the lateral Cherenkov light distributions. This allows enhanced multi-parameter investigations of air shower properties from which the primary cosmic ray composition can be inferred.

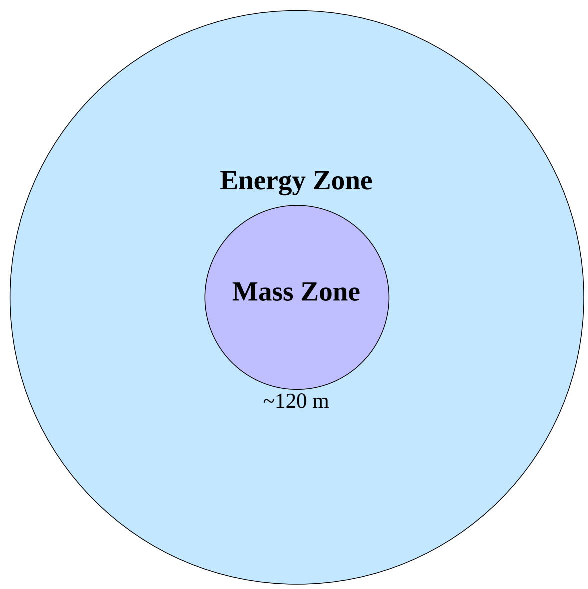

Figure 1: The two zones of a Cherenkov lateral distribution from an EAS, as seen from along the shower core. The inner ("mass") zone is sensitive to primary mass and energy, while the outer ("energy") zone is sensitive mostly to primary energy. The outer radius of the energy zone is determined by the energy of the shower and the threshold of the detector.

2 Experimental Technique

The ability to make multi-parameter measurements of extensive air shower properties has been long recognized as an important tool in the identification of the primary. The program we have developed at Soudan involves making simultaneous measurements of underground muon fluxes and surface Cherenkov distributions.

2.1 Cherenkov Light The electromagnetic portion of an extensive air shower contains important information about the energy and mass of the primary particle. For instance, the total number of EM shower particles scales with the primary energy, while the depth of the maximum shower development in the atmosphere, X_{max}, is sensitive to the primary mass *and* energy. These dependencies are thought to be relatively insensitive (cf. muon simulations) to differences in hadronic interaction models (Lindner, 1997 and Cortina, 1997). However, because traditional air shower arrays sample the electromagnetic cascade at only a single plane along its longitudinal development, typically well past X_{max}, it is problematic to reconstruct from these measurements the actual shower properties.

Cherenkov light measurements can provide information which traditional air shower arrays cannot. Because Cherenkov light is emitted throughout the longitudinal development of the EAS, the Cherenkov light field contains information about the characteristics of the shower, such as its total size and depth of X_{max}. The efficacy of the so-called "Cherenkov Technique" rests on the conclusion that the Cherenkov lateral distribution (Figure 1) can be divided into two regions.

In the outer region, at distances $R \gtrsim 120$ m from the shower core, the Cherenkov pulse height depends primarily on the size of the EM cascade; that is, on the energy of the extensive air shower. In the inner region, $R \lesssim 120$ m, the pulse height depends not only on the air shower energy, but on the depth of maximum air shower development, X_{max}, as well. This result, which was first identified by Patterson and Hillas (Patterson and Hillas, 1983), has been well-documented (e.g., Lindner, 1997 and Watson, 1997), and frequently exploited (e.g., Fortson, *et al.*, 1997 and Boothby, *et al.*, 1997 and Plaga, *et al.*, 1995).

With a minimum configuration of two widely-spaced detectors, then, one in the inner, "X_{max}" zone, and one in the outer, "energy" zone, a simultaneous estimate of both air shower energy and depth of maximum development can be obtained.

2.2 Muon Production Muon production too, is a function of the primary's mass and energy. At a fixed energy, heavy nuclei are known to generate more muons than lighter nuclei. Thus, if the energy of an air shower is known, a measurement of the associated muon flux can provide an estimate of the primary particle's mass.

Simulated muon properties are sensitive to hadronic Monte Carlo ideosyncrasies. Multiplicities and angular distributions are known to vary from code to code and there is no experimental accelerator data to favor any particular approach. Recently, new results (Mualem, *et al.*, 1999) have emerged which challenge the muon production accuracy of several standard hadronic interaction codes. This issue warrants serious consideration and underscores the importance of *multi*-parameter measurements of air shower properties, where simulation biases can hopefully be offset.

2.3 Analysis Strategy The analysis strategy we have employed to interpret the coincident event data (i.e., coincidences between Soudan 2 and the Cherenkov array) proceeds as follows.

From muon tracks in the underground detector, the underground shower core location and trajectory are estimated. This trajectory is projected back to the surface of the earth and the surface core location is marked. If the shower core at the surface is within 120 m of one detector (i.e., in the X_{max}zone) and further than 120 m from the other detector (energy zone), it is labeled a 'gold' event. From the signal in the "far" detector, an estimate of the air shower energy is obtained. This energy estimate, which is accurate to approximately 20%, along with the signal collected in the "near" detector, yields an estimate of the $X_{max}$of the shower. The energy plus X_{max}then yields an estimate of the primary mass. The total muon multiplicity, as extrapolated from the muon count in Soudan 2, along with the energy estimated from the Cherenkov array, yields another estimation of the primary mass.

Thus, for every "gold" event, we can generate two independent estimates of primary mass. They are independent in the sense that each is based on the measurements and simulations of a different component of the extensive air shower. This acts to identify and correct for any potential biases present in the detection or simulation of each individual component.

3 Hardware Description

3.1 Soudan 2 The Soudan 2 detector (Allison, *et al.*, 1996) is a modular one-kiloton iron-core tracking calorimeter located in an iron mine in northern Minnesota. The detector is at a depth of 710 m (2100 mwe) below the surface of the earth, where the overburden provides an effective muon energy threshold of $\sim$ 1 TeV. Designed to detect proton decay, Soudan 2 has a position resolution of $\sim$ 1 cm. Full muon tracks can be reconstructed to an angular accuracy of roughly $0.25°$. The main detector has a modest 9 m $\times$ 14 m footprint, but is surrounded by an active veto shield of proportional tubes measuring 14 m $\times$ 31 m. Muon events are registered in the main detector at a rate of $\sim$ 0.2 Hz.

3.2 Cherenkov Array The Cherenkov array at Soudan consists of two detector stations located on the surface above the main calorimeter, separated by 110 m. Each station contains twelve hemispherical photomultiplier tubes, 12.5 cm in diameter. Every tube is fitted with a 25.0 cm Winston cone, which increases its effective area by a factor of four. The phototubes are housed in detector enclosures suitable for protection from the harsh Minnesota climate; they feature motor-driven removable roofs to protect the tubes from adverse weather conditions and daylight.

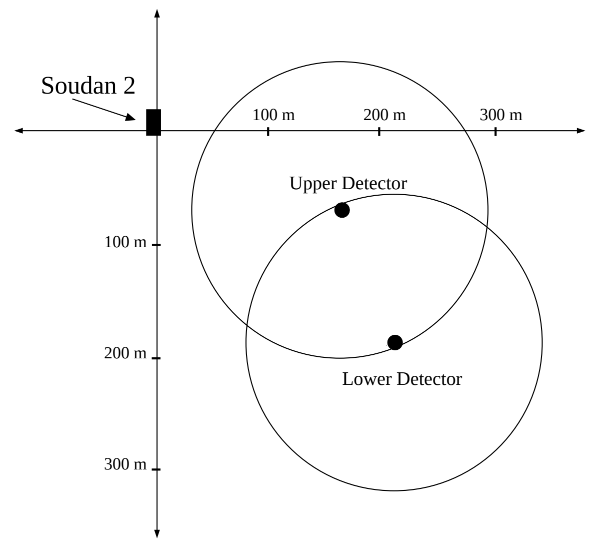

Figure 2: Map of the Soudan site. Shown are the two Cherenkov detectors and Soudan 2. The circles around the Cherenkov detectors represent the boundaries between the mass and energy zones of a Cherenkov lateral distribution.

The array is self-triggered, with two thresholds set dynamically to adjust to ambient night sky light levels. Cherenkov-only triggers occur at rate of ~ 0.05 Hz, while the Cherenkov-Soudan 2 coincidences have a rate of approximately one every 10 minutes.

The photomultiplier signals are digitized at 100 MHz and read out by a data acquisition computer. All event information, including timestamp, voltage and current levels, threshold settings, and digitized signals are written to persistent data objects for off-line analysis.

The detectors are fully automated, with each station utilizing independent computer-controlled high voltage and watchdog safety systems. Nightly operation begins when ambient light levels drop below threshold. The enclosure roofs are then opened and the high voltage on the phototubes is set. Trigger thresholds are then determined, and data acquisition begins. Over the course of an evening, the system will adjust for changes in night sky light levels by changing the array trigger thresholds. In the event of an excessive light level condition, the roofs are closed and the system hibernates until conditions improve. Table 1 lists some of the specifications of the detector.

4 Software Description

As in any indirect cosmic ray experiment, Monte Carlo simulations play an important role in our studies. Several codes were used in this investigation to model the behavior of EAS. Hadronic interactions were handled by the NUCLIB (Engel, *et al.*, 1992), SIBYLL (Fletcher, *et al.*, 1994), and TARGET (Kertzmann and Sembroski, 1994) codes. Electromagnetic and Cherenkov simulations were performed using the CHESS routine, developed at Minnesota (Vassiliev, *et al.*, 1997).

The data acquisition and analysis software is written using modern, object-oriented development methods. Data acquisition applications are written using Visual C++ with appropriate library extensions for hardware interfacing. The analysis software uses Digital C++, with extensive use of the ROOT analysis package (Brun and Rademakers, 1997).

5 Results and Conclusion

We have built a new dual non-imaging Cherenkov array to operate in coincidence with the Soudan 2 underground tracking calorimeter. This array provides a powerful tool for measuring cosmic ray composition in the knee, by providing multi-parameter measurements of extensive air shower properties. The array, which is an extension of the long-standing cosmic ray program at Soudan, has operated during the winter months for the last 1.5 years. Though hampered over this time period by poor weather conditions, several hundred surface-underground coincident events have been collected. Initial analysis of the data is currently under way. Preliminary results on the estimated mass of cosmic rays throughout the knee region will be presented at the conference.

Location	47.8° N, 92.2° W
Atmospheric depth	978 g/cm^2
Distances to Soudan 2	745 m
Zeniths w.r.t. Soudan 2	13.9°, 20.9°
Array spacing	110 m
Tubes/Detector	12 (EMI 9870)
Total collecting area	1.2 m^2
PM operating gain	$0.5 - 2.0 \times 10^4$
Trigger threshold	$2.0 - 2.5 \times 10^3\ PE$
Digitizing frequency	100 MHz
Digitizer depth	40.96 μs
Dead time (read out)	200 ms
Live time fraction	$\sim 94\%$
Time resolution (WWVB clock)	1 ms
Noise rate per tube	8 $PE/nsec$
Maximum background current	$< 55\ \mu A/tube$
Data rate:	
free-running	$0.045 - 0.10\ Hz$
coincidences	$4 - 6$ *per hour*
Average duty cycle (winter)	~ 3 %

Table 1: Dual Cherenkov Array Specifications.

6 Acknowledgements

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