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Simultaneous Observations of Extensive Air Showers and Underground Muons at Soudan 2*

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We have built a small proportional tube air shower array on the surface above the Soudan 2 proton decay detector in Soudan, Minnesota, U.S.A. This array, in coincidence with the underground detector, allows simultaneous surface and underground observations of high energy cosmic ray showers. These observations, still in their initial stages, may eventually be able to provide information about the composition of cosmic ray primaries in the "knee" region of the energy spectrum.

I. Introduction

The "knee," the region of the cosmic ray energy spectrum just above 10^{15} eV where it undergoes a sudden steepening, is of great interest to modern cosmic ray physics. Understanding the cosmic ray primary composition in this region may lend insight into the problems of ultra high energy cosmic ray origin and acceleration, and to the source of the knee itself.

Unfortunately, direct composition measurements at these energies are difficult due to the extremely low flux of primaries. This has resulted in an indirect approach to the problem, generally focused on trying to recreate the primary composition through analysis of the extensive air shower it initiates in the atmosphere. Recently, a few

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experiments have begun to refine this idea by simultaneously examining the extensive air shower and the deep underground muon components of ultra-high cosmic ray interactions[1]. This is one such experiment.

II. Experimental Apparatus

The Soudan 2 proton decay detector[2] is a large tracking drift calorimeter located 713 m beneath the surface (2090 mwe) in a non-operational iron mine in Soudan, Minnesota, U.S.A. (latitude 47.82° N, 92.25° W). Still under construction, its size was 10 m x 8 m x 5 m high during the time interval discussed here. The cosmic ray-induced muon directional resolution of the Soudan 2 detector is about 1.2°, corresponding to a lateral distance of about 15 m in projection onto the surface.

The Soudan 2 surface array is a small (40 m^2) proportional tube array located in a converted house trailer on the surface at the Soudan mine site. It is situated 713 m above, 50 m south and 140 m east of the underground calorimeter, about 12° from vertical.

The array itself consists of 32 8" x 2" x 22' long proportional wire modules, arranged in two groups of 16 each, separated by about 3 m. Each module contains 15 separate 1" square proportional tubes arranged in two parallel overlapping layers. The 480 individual wires are ganged into 240 1" x 2" x 22' long channels. They are operated in an on/off mode and have no spatial resolution in their length. The surface array is triggered and read out along with the underground detector.

This arrangement provides a measure of the average particle density at the surface array for each event that triggers Soudan 2. Using the underground tracks to define the direction of the cosmic ray shower, one can calculate the perpendicular distance from the shower core to the surface array, and then determine the shower size at surface detector depth through well-known cosmic ray shower density profiles[3]. The total shower energy can be estimated from its size.

III. Data

The Soudan 2 surface array first began recording data in May, 1991, and has been fully operational since mid June, 1991. It has run regularly since that date, with breaks for detector installation and maintenance. The data discussed here were acquired over 50.4 live hours from the evening of 3 July to the morning of 6 July, 1991. They are only a small part of the total set, but sufficient to illustrate some characteristics of the Soudan 2 surface-underground coincidence experiment.

For each cosmic ray muon event which triggers the Soudan 2 detector, a 128 μs long window is examined in the surface detector data. Events with two or more separate two-layer tracks are retained. The data contain 1275 such events. The time at which the trigger reaches the surface array (corrected for trigger generation delay) is set to 0, and the resulting time distribution is shown in figure 1a.

The delay between the center of the peak and the surface detector trigger time, about 7 μs, is consistent with the travel of near light-speed particles approximately 700 m underground, plus the return of a trigger signal the same distance over a twisted pair data line. The width (fwhm) of the peak is 2 μs, consistent with the expected jitter of +/- 1 μs in both the above- and below-ground timing determinations. The peak contains 337 events in the 4 μs interval [-9 μs, -6 μs]. The off-peak background is 7.56 +/- .25 events/μs. Figure 1b is an identical timing plot for 794 random triggers in the Soudan 2 detector. It has no corresponding peak.

As a further check of the ability of Soudan 2 to make simultaneous measurements of above- and below-ground cosmic ray showers, the spatial characteristics of the above data were examined. Figure 2a and 2b are plots of the projected intersection points of cosmic ray shower cores and the horizontal plane containing the surface detector. The origin is directly above Soudan 2, and north is roughly along the +z axis. Figure 2a contains the 337 events in time coincidence with the surface array (those in the peak of figure 1a). and figure 2b contains the 938 out-of-time events (the background in figure 1a).

Surface showers recorded during cosmic ray induced underground muon events in Soudan 2 show a time structure consistent with coincident above- and below- ground observations of the same cosmic ray shower. Random triggers show no such structure. In addition, those showers in a designated 4 μs coincident window [-9μs, -6μs] have a clear tendency to group spatially around the measured position of the surface array, while those outside the coincident window do not.

There are 307 (above background) in-time events over 50.4 hours, corresponding to a coincident above- and below-ground cosmic ray shower event rate of 53 400 +/- 3000 per live-year. As of early August, 1991, about 5000 such events have been recorded.

Although the underground multiplicity distributions and shower size determinations made from these data are of great interest, their analyses have not yet been corrected for systematic effects, and so are not presented here.

IV. Conclusions

As the Soudan 2 surface array has just become operational, the data so far are necessarily preliminary. In particular, further work must be done in determining the multiplicities of the underground tracks and in reconstructing the shower size from the surface array data. The high data rate and beginning analysis, however, are quite promising. As this work progresses, we will be able to compare our data to extensive studies of high energy showers in the literature[4]. The near future will determine whether this experiment can make inroads into the relatively unknown territory of ultra high energy cosmic ray primary composition.

References

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Figure 1a

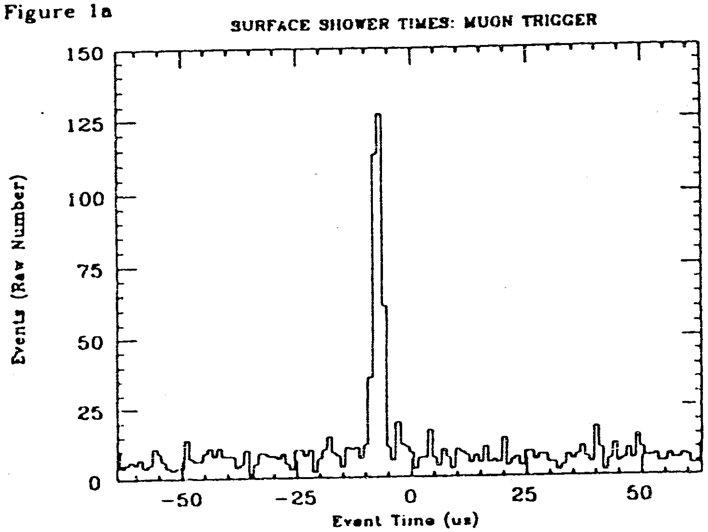


Figure 1b

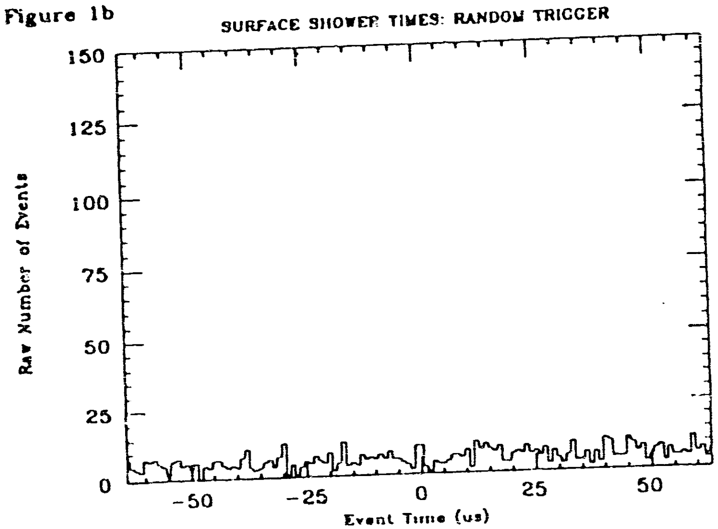


Figure 2a

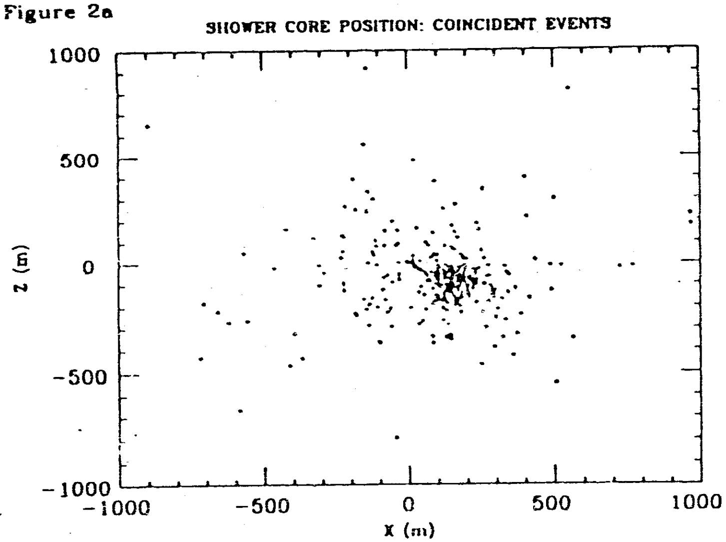
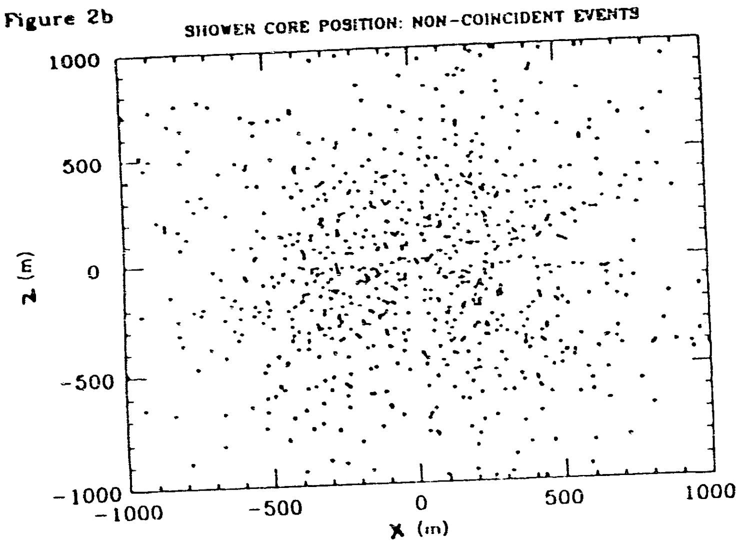


Figure 2b



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