Composition of Cosmic Rays from Coincidences Between Air Showers and Muons in the Soudan2 Detector

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Abstract

A small array of charged particle detectors above ground was run in coincidence with the Soudan2 underground detector from 1999 to 2000. Almost 4600 coincident cosmic ray events were analyzed with primary energy between 10^{14} and 10^{17} eV. The energy was determined from the density of particles in the surface array: groups of scintillator modules and proportional tubes. By analyzing the number of underground muons and comparing with air shower Monte Carlo simulations, the cosmic ray composition in this energy range was estimated. These data suggest the nuclear composition remains mixed up to at least 10^{15} eV.

1. Description

The surface air shower array[3] consisted of four groups of detectors: two groups of proportional tubes with a total area of 36 m^2, and two groups of 1 m^2 scintillator modules, six in each group. Each scintillator group was approximately 30 meters from the proportional tubes, one each to the east and west.

We operated these detectors in coincidence with the Soudan2 underground detector in northern Minnesota, USA, a high resolution 1 kiloton tracking calorimeter which was used to study neutrino interactions, search for proton decay, and for cosmic ray and astrophysics studies[1]. The resolution of particle tracks in the main detector was very good; analysis of the resulting tracks were limited by multiple scattering in the overburden to ± 0.3 degrees. The total area of the detector as seen by cosmic rays was approximately 120 m^2.

The surface detectors were 490 meters above sea level, and were located 710 meters above the Soudan2 detector. The threshold (50% probability) for vertically incident muons to reach the underground detector was 700 GeV.

2. Data

The arrangement of detectors described here collected data from April 1999 until October 2001, though they did not run continuously during that time. The actual live time for this data sample was 277 days and consisted of 12 million

pp. 127–130

Soudan2 triggers.

Events were selected that were within a 4 microsecond coincidence window and had at least one reconstructed muon in the Soudan2 detector. I also required a minimum number of hits in the surface detectors: at least 2 hits in each of the two groups of proportional tubes, and two hits in one scintillator group and one hit in the other scintillator group. After applying these requirements, 4598 events remained in the data sample. Analysis of the out-of-time data suggest that 16 of these events were accidental coincidences.

One final cut was very severe. A detector readout limitation, not statistics, sets the upper energy available in this analysis. Very large multiple muon events in Soudan2 were not completely saved to disk; the detector was optimized for small events such as proton decay and neutrino interactions. Almost all events with less than 12 muons were retained, but an increasing fraction of events with more muons than this were absent from the data. I elminated events with more than 12 underground muons from further analysis.

These data were compared to two Monte Carlo data samples generated assuming an all proton and an all iron composition. I simulated air showers using the CORSIKA simulation package[4] and the QGSJET hadronic interaction model[5], though DPMJET [6] was also considered. I used Geant4 [2] to track high energy muons through the overburden to the Soudan2 detector, taking into account the surface topography and the known properties of the rock.

3. Analysis

Three pieces of information are needed from the underground detector: the number, location, and direction of the muons. The estimate of cosmic ray composition depends on the number of muons, while a reconstruction of the surface air shower size requires the location of the shower core based on the direction and position of the muons.

Unlike large air shower experiments, the core location can not be determined from the surface data. Instead, I projected the underground muon tracks back to the surface, and I calculated the distance from this location to each surface detector group. Finally, these four values for the air shower density at four distances were compared with shower profiles from Monte Carlo air shower simulations assuming a proton primary and an estimate for this proton's energy (E_p) was obtained. The energy resolution was roughly ± 0.25 $\log(E_p/eV)$: one bin on the data plots presented here.

The number of underground muons was determined from the Soudan2 tracking software and errors in the counting or track reconstruction were corrected by scanning each event. For events with fewer than 5 muons the reconstruction was essentially perfect; with more muons the uncertainty was still very small, contributing no more than $\pm 2\%$ to the average number of muons per event.

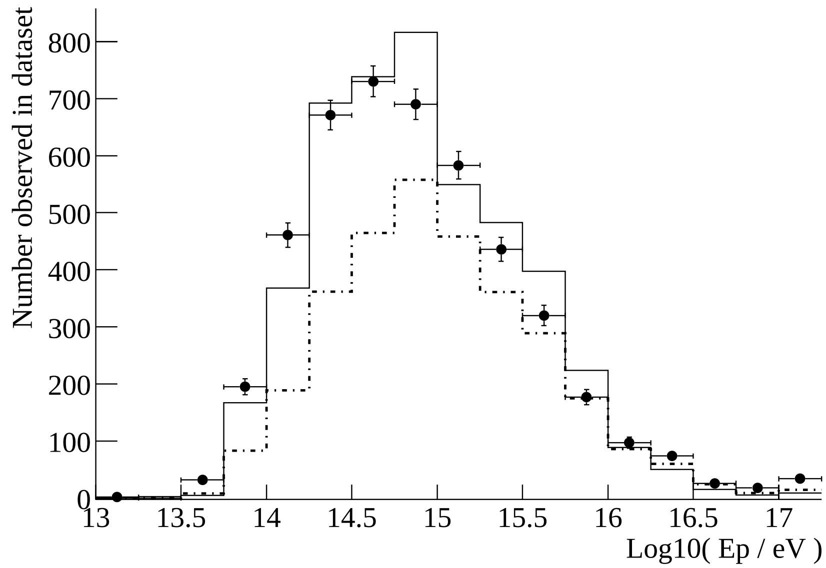

Fig. 1. Histogram of reconstructed energy for data (points), Monte Carlo protons (solid) and iron (dashed). The error bars on the data are statistical only.

4. Results

In figure 1, the 4598 events are binned by reconstructed shower energy. The highest energy bin in this plot contains mostly accidental or mis-reconstructed coincidences, and is ignored in this analysis. Because I assume a proton primary when estimating the energy, the result really refers to "shower size" and not the actual energy of the primary particle. The data and the Monte Carlo are treated identically in this respect, and iron primaries are reconstructed with "proton energy (E_p)" typically one bin lower than their true energy. The Monte Carlo is normalized so the data and the proton curve contain the same number of events.

Figure 2 illustrates that these data are consistent with a mixed composition up to 10^{15} eV. It shows the average number of muons for different energy bins compared with the Monte Carlo prediction for all-proton and all-iron compositions. The iron prediction is the upper one at lower energy. The plot also shows that there is no sensitivity at $10^{15.5}$ eV where the Monte Carlo predictions cross because events with more than 12 muons were cut.

In Figure 2, the error bars on the data include statistical and systematic uncertainties and the gray bands indicate the systematic uncertainty in the the Monte Carlo. The uncertainty in the Monte Carlo was studied two separate ways. I compared the QGSJET results with the DPMJET interaction model and saw a difference between 1% at lower energies and 3% at higher energies, DPMJET was always lower. I also scaled the transverse momentum distribution of the high

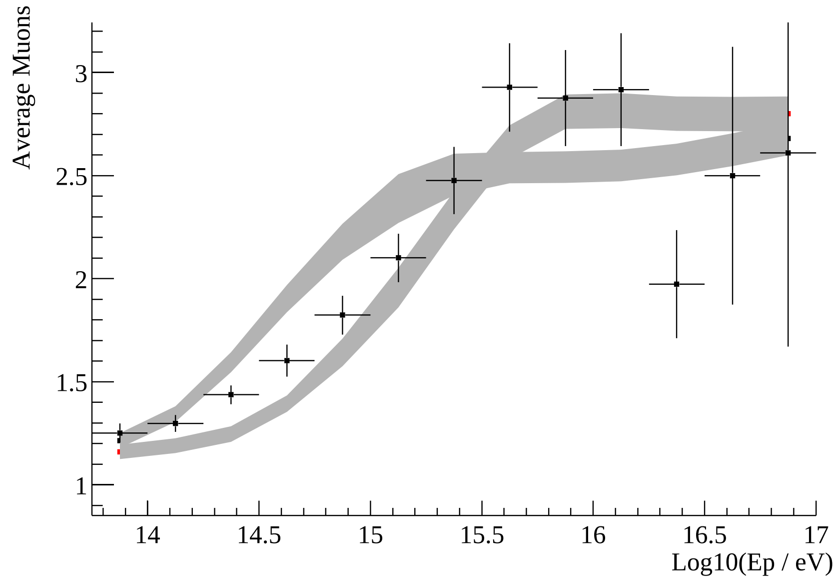

Fig. 2. Average number of muons in Soudan2 for data (points) Monte Carlo protons (lower band at lower energy) and iron (upper band at lower energy).

energy muons, in effect making the muon bundles more or less spread out. A 10% change in the $p_\perp$ distribution had a $\pm 4\%$ effect through most of the lower part of the plot. This effect is more significant than the total number of muons because of the finite size of the detector and many events are centered some distance away.

5. Conclusion

These data suggest that the composition of cosmic rays just below the knee in the energy spectrum is mixed, consistent with other experiments. The experiment loses sensitivity around 10^{15} eV due to technical issues and not due to statistics or fundamental limitations of this technique. A future underground experiment with similar multiplicity resolution, size, and depth could clarify issues about the cosmic ray composition or the hadronic interaction model.

6. References

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