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Measurements of the muon component of extensive air showers at 320 m.w.e. underground

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Abstract

The ALEPH detector at LEP has been supplemented with five scintillator telescopes to measure the muon component of cosmic ray air showers underground. The emphasis of the present analysis of a new data set is to measure coincidences over distances up to about 1 km which are sensitive to the forward production of hadronic interactions and the chemical composition of primary cosmic rays in the energy range around 10^{15} eV. First results indicate that the observed decoherence curve of muons is compatible with a light primary composition and the arrival directions of muons show no obvious clustering in galactic coordinates.

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Keywords: Cosmic ray; Muon; Composition; Shower; Galactic

1. Introduction

The origin of high-energy cosmic rays is still an open question and is of great astrophysical interest. Supernova explosions are good candidates, which can explain the bulk of cosmic rays measured near the Earth and their acceleration up to energies of about a few PeV (so-called 'knee' region). Well above this energy cosmic rays might be of extragalactic origin [1].

Recent measurement [2] indicate that the 'knee' is caused by a rigidity-dependent cut-off of individual species of primaries. In general, the elemental composition of primary cosmic rays is closely connected to the acceleration and propagation mechanisms in the galaxy.

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It is therefore of interest to investigate the high-energy component of cosmic rays to possibly locate the accelerators in the sky. However, the problem is complicated by the fact that time-dependent irregular magnetic fields in our galaxy and beyond obliterate the original direction of emission of charged particles. Eventually the aim of this analysis is to estimate quantitatively the chemical composition of primary cosmic rays in the energy region around the 'knee', where CosmoALEPH has the best sensitivity. In addition, the measurement of the arrival times of high-energy muons in dedicated CosmoALEPH runs along with the high precision information from the Time Projection Chamber (TPC) allows one to infer the arrival directions of energetic primaries.

2. Experimental setup

The CosmoALEPH experiment [3,4] installed in the ALEPH pit of the electron–positron storage ring LEP at CERN uses the ALEPH detector and five scintillator telescopes in the pit and the LEP tunnel to measure the muon component of Extensive Air Showers (EAS) underground. CosmoALEPH is sheltered by an overburden of 320 m water equivalent corresponding to a momentum cut-off of about 70 GeV for vertical incidence. Details of the experimental setup, the trigger and data acquisition systems have been described elsewhere [5,6]. Additional data sets are available from the years 1995–1998 [7], which are not included in this analysis. The bulk of the data analyzed here were taken between May 2000 and November 2000. During the data taking period about 1.8×10^8 events were collected with all detector stations within a time window 200 μs and in addition 1.4×10^6 events were recorded in the TPC in dedicated CosmoALEPH runs in the year 1999.

3. Measurements of the decoherence curve

3.1. Experimental results

The basic characteristic of EAS underground is the lateral distribution of muons. This parameter is sensitive to the chemical composition of primary cosmic rays, their energy and the interaction characteristics. The distributions of muon arrival time differences for some pairs of stations are shown in Fig. 1. The signals of muon coincidences are clearly seen and indicate the presence of extended air showers over distances up to ~ 300 m. The background-subtracted coincidence rates per unit station area per unit time have been corrected for detector inefficiencies (see Table 1). From the coincidence rates between various detector stations the lateral distribution of air shower muons can be inferred. This is usually done by showing the decoherence curve, as shown in Fig. 2.

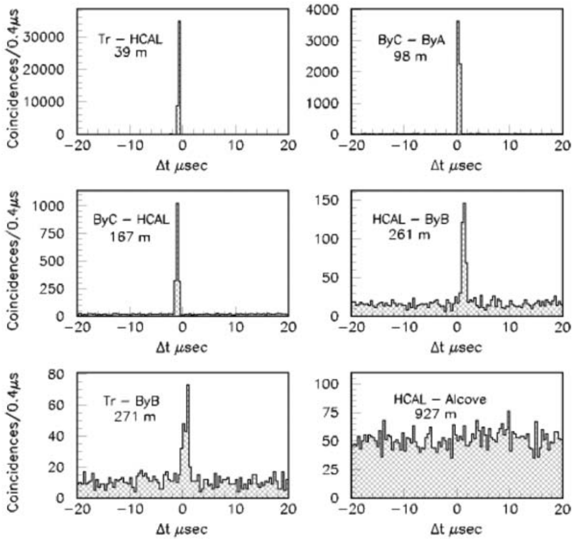

Fig. 1. The arrival time differences of muons for different pairs of stations measured with CosmoALEPH. The distances between stations in each pair are indicated in the figure. The shift of the coincidence peaks from $\Delta t = 0$ μs is due to different cable lengths at the individual stations which have so far not been corrected for.

3.2. Monte Carlo simulation

For the CosmoALEPH experiment the muon flux underground at the detector level drops by two orders of magnitude with respect to the flux at the surface. For this reason a full simulation of the experiment seems to be impractical due to limited

Table 1
Characteristics of stations in the CosmoALEPH setup

Station	Bypass C	Trolley	Bypass A	Bypass B	HCAL	Alcove
Area (m^2)	3.6	4.5	5.28	6.69	9.4	7.04
Efficiency (%)	76	75	74	86	85	74
Uptime (days)	156.9	157.5	158.1	129.7	145.4	152.9
Rate (Hz)	1.25	1.52	2.02	1.18	2.11	3.56

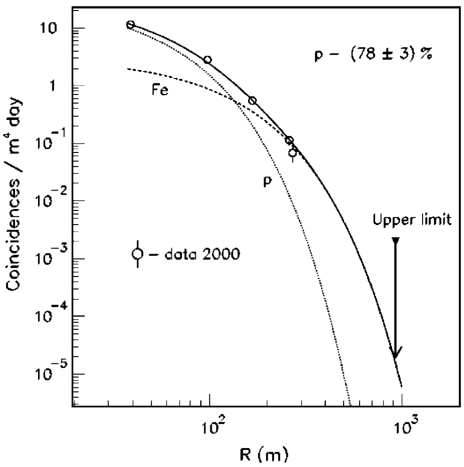

Fig. 2. Normalized coincidence rates between unit effective areas as a function of distances R between the detector stations. The solid line is a preliminary Monte Carlo fit to the data based on predictions for p- and Fe-induced showers separately. The dotted line represents the contribution of p-induced showers and the dashed line displays the contribution of Fe-induced showers. The symbols represent the new data set (statistical errors only).

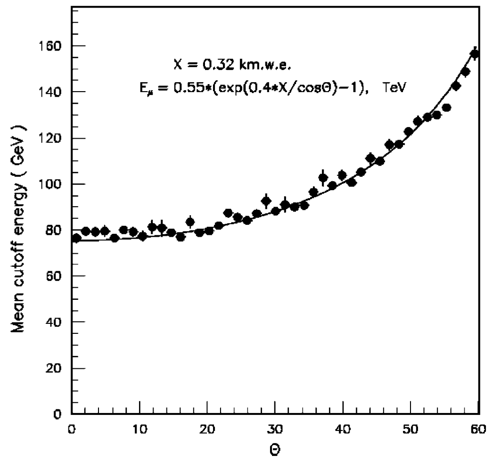

Fig. 3. Mean cut-off energy of muons in the rock as a function of the zenith angle. Black symbols are the results of a simulation using GEANT and the solid line is the best fit with an exponential function.

computing resources. A fast simulation program based on parameterizations of basic features of EAS [8,9] has been developed and used in the present analysis.

Large samples of events are generated for proton ($\sim 4 \times 10^9$ events) and iron ($\sim 5 \times 10^8$ events) induced showers with energies between 1 and 10 PeV and zenith angles ranging from 0° to 60°.

The propagation of muons through the overburden is simulated using the CERN package GEANT. Fig. 3 shows the muon cut-off energy in the rock and Hadron calorimeter (HCAL) of ALEPH as a function of the zenith angle obtained from a simulation for a slant depth of 320 m.w.e. under the assumption of a flat homogeneous overburden. The solid line is a fit to the Monte Carlo results with an exponential function taken from [8]. Further, this parameterization has been used for the simulation of the threshold energy of muons traversing the overburden. The spectral contributions of different elemental components of the primary spectrum in the energy region of interest have been measured by cosmic-ray experiments on the surface [10]. We show our preliminary underground data in Fig. 2 in comparison to a model which assumes that only two components (p, Fe) contribute to the observed decoherence curve. Our data are best described by a proton fraction $f_p = 0.78 \pm 0.03$, where the error is only statistical. Systematical errors, e.g. due to detector inefficiencies, are still being evaluated.

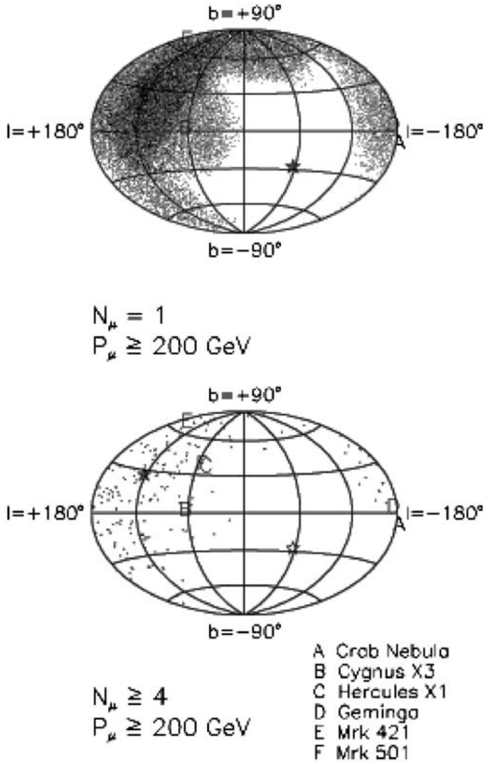

Fig. 4. Arrival directions of muons with energies above 200 GeV and multiplicities $N_\mu = 1$ and $\geqslant 4$ in galactic coordinates b (latitude) and l (longitude). The stars show the positions of the Celestial North and South Pole. For comparison some known gamma-ray sources of galactic and extragalactic origin are given as letters A–F. The special hit pattern is caused by the convolution of geometrical acceptance and exposure time for the various regions in the sky.

3.3. Muon arrival directions

Observations of cosmic ray events near EeV energies appear to indicate that there is an enhancement of arrival directions of cosmic rays from the galactic center and the Cygnus X-3 region [11]. Therefore, a search for possible non-random directions in the form of clusters on the sky using events with high momentum muons might be promising. For this purpose, the ALEPH TPC with an excellent angular resolution of a few milliradian and good momentum resolution $\Delta p/p^2 < 0.1\%\,\mathrm{GeV}^{-1}$ is used. The arrival directions of muons with energies above 200 GeV and muon bundles with different muon multiplicities in galactic coordinates are plotted in Fig. 4. No evidence of clustered events is found in the regions of known astrophysical sources in our galaxy or nearby galaxies. This is consistent with the expectation that most of the muons are created by interactions of charged cosmic ray primaries in the energy range around 10^{15} eV.

4. Conclusion

The observed lateral distribution of cosmic-ray muons at an underground depth of 320 m.w.e. can be described by a dominant light composition of primary cosmic rays. A fit of the decoherence data to a two-component mass composition of proton and iron gives a proton fraction $f_\mathrm{p} = 0.78 \pm 0.03$, where the error is only statistical. Systematic errors are still under study. The arrival directions of individual energetic muons and muon bundles do not show any correlation with known sources.

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