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NUCLEAR PHYSICS B
PROCEEDINGS
SUPPLEMENTS

Identification of light and very heavy cosmic ray primaries at $E_0 \approx 10^{15}$ eV from surface and deep underground measurements at the Gran Sasso Laboratories

THE EAS-TOP AND LVD COLLABORATIONS*

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'Very heavy' (iron-like) and 'light' (proton-like) cosmic ray primaries are identified at primary energies $E_0 \approx 10^{15}$ eV by means of simultaneous measurements of shower size N_e, $N_\mu{}^{GeV}$ $(= N_\mu(E_\mu > 1\ GeV))$ at the surface, and $N_\mu{}^{TeV}$ $(= N_\mu(E_\mu > 1.3\ TeV))$ and $\Delta E_\mu/\Delta L$ (i.e. muon energy losses per unit of track length) at the Gran Sasso Laboratories by EAS-TOP at the surface (2000 m a.s.l.) and LVD deep underground (3400 m $w.e.$ depth). 'Very heavy' primaries are selected using large muon numbers detected by LVD; 'light' primaries using high muon energy losses in the LVD scintillation counters, the two selections operating in two different predefined ranges of N_e. Their identification is confirmed from the analysis at the surface in the $N_e - N_\mu{}^{GeV}$ domain, by their 'location' in regions of 'high' and 'low' muon numbers. The experimental points lay around the average predictions from the CORSIKA-HDPM code.

This procedure provides the first interpretation of individual events at such primary energies through the Extensive Air Shower technique, and the verification (at least on average) of the CORSIKA-HDPM code.

The presence of iron-like primaries is proved up to primary energies $E_0 \approx 5.10^{15}$ eV.

1. INTRODUCTION

A main problem in the study of cosmic rays at the highest energies is given by the nature of Extensive Air Shower (EAS) measurements, whose interpretation is hard, due to the difficulties of separating hadronic physics from composition effects, by the role of the fluctuations intrinsic in the detection technique, and the lack of absolute calibrations. A main improvement in such direction is of performing multicomponent observations of EAS and of analyzing a sample, although small, of individual events. This is one of the aims of the EAS-TOP experiment at the Gran Sasso laboratories and its correlated measurements with the detectors operating in the underground laboratories (EAS-TOP Coll., 1997a).

The present data include measurements from the electromagnetic (shower size, N_e) and muon detectors $(N_\mu{}^{GeV} = N_\mu(\tilde{E}_\mu > 1\ GeV))$ of EAS-TOP and $(N_\mu{}^{TeV} = N_\mu(E_\mu > 1.3\ TeV))$ and $\Delta E_\mu/\Delta L$ (i.e. muon energy losses per unit of track length) from LVD deep underground. Events candidate for being originated by 'light' (proton-like) or 'very heavy' (iron-like) primaries are selected from their characteristics in the EAS-TOP (N_e) and LVD ($N_\mu{}^{TeV}$) domain. 'Light' primaries are selected from high muon energies, deduced from their large energy losses in LVD, and relatively small N_e (indicating high energy/nucleon of the primary). 'Very heavy' primary candidates are selected from high muon multiplicities in a specified shower size interval. Such events are studied at the surface following the $N_e - N_\mu{}^{GeV}$ data. In both cases, although in different primary energy ranges, they fall on the average expected regions for the respective primaries.

2. THE EXPERIMENTS

EAS-TOP is an EAS array located at 2000 m a.s.l., 30^0 from the zenith of the underground Gran Sasso laboratories. Its e.m. detector is

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made of 35 modules scintillator detectors 10 m^2 each spread over an area of 10^5 m^2 (Aglietta et al., 1988 and 1993). The shower size (N_e) is measured for events internal to the edges of the array, through a fit of the l.d.f. providing also the core location, with accuracy $\sigma_{N_e}/N_e \approx 10\%$ for $N_e \geq 2{\cdot}10^5$. The muon detector is a 144 m^2 tracking module (EAS-TOP Coll., 1995). ${N_\mu}^{GeV}$ represents the total muon number with $E_\mu > 1\ GeV$, obtained from the number of muons recorded in the muon detector (n_μ) and the experimental average l.d.f. constructed at the zenith angle of $25 - 35^o$ (EAS-TOP Coll., 1997b).

LVD is a large volume of liquid scintillator (Aglietta et al., 1992) interleaved with limited-streamer tubes (Aglietta et al., 1994) in a compact geometry, that combines high tracking capabilities with good energy loss measurements (LVD Coll., 1997) located in the underground Gran Sasso laboratories. In the present analysis 304 scintillator counters, for a total area of 78 m^2, are considered.

Due to the lack of information on the EAS core location deep underground, ${N_\mu}^{TeV}$ is the detected muon number, and therefore represents a lower limit to the total muon number with $E_\mu > 1.3\ TeV$.

$\Delta E_\mu/\Delta L$ is the muon energy released in the LVD scintillator counters ($1.5 \times 1 \times 1$ m^3 seen by three photomultipliers) normalized to the track length ΔL in the scintillators, obtained from the tracking system with accuracy within 1%. The energy resolution is about 15% for a 10 MeV energy release (Aglietta et al., 1992).

The data have been collected in 14200 h of running time between June 1992 and December 1996.

A set of data comparable with the experimental ones has been simulated by means of the CORSIKA code (HDPM model, version 4.502 Capdevielle et al., 1991) for proton and iron primaries ($\gamma_p = \gamma_{Fe} = 2.62$). The muon propagation in rock is simulated by means of the MUSIC code (Antonioli et al., 1997). The full response of the detectors is included.

3. ANALYSIS AND RESULTS

The experimental $N_e - {N_\mu}^{GeV}$ scatter plot is shown in Fig. 1; the average expectations from the simulations for proton and iron primaries are also shown. On the basis of the above considerations, 'very heavy' and 'light' enriched primary beams are selected respectively through:

(a) large ${N_\mu}^{TeV}$ muon numbers:

${N_\mu}^{TeV} > 2.4\ LogN_e$ - 7.4 for $N_e > 2 \cdot 10^5$, i.e. with low probability of being due to fluctuations of light primaries, as obtained from the quoted simulation;

(b) large muon energy losses: $\Delta E_\mu/\Delta L > 4\ MeV/cm$ in the highest and lowest counter crossed by the track inside the detector. Only events with ${N_\mu}^{TeV} = 1$ and with $N_e < 2 \cdot 10^5$ are considered. In such conditions the fraction of events giving energy losses $\Delta E_\mu/\Delta L > 4$ MeV/cm simultaneously in the top and bottom counters of LVD crossed by the track is 0.7% for proton primaries and 0.1% for iron primaries. The $N_e - {N_\mu}^{GeV}$ relations at the EAS-TOP level for such selected events a) and b) are shown in Fig. 2, together with the average expectations from the CORSIKA-HDPM code. The statistics is strongly reduced, but the remaining events clearly identify regions of large and small muon numbers in the $N_e - {N_\mu}^{GeV}$ scatter plot, as expected respectively from 'very heavy' and 'light' primaries. The probabilities that the ${N_\mu}^{GeV} - N_e$ distributions for the selected p-like and Fe-like candidates are sampled from the experimental all data distribution of Fig. 1 are, for both cases, lower than 1%. The CORSIKA-HDPM code reproduces fairly well the average behaviours. Also by means of the quoted simulation it has been verified that for given primaries the fluctuations in the GeV and TeV muon numbers (${N_\mu}^{GeV}$ and ${N_\mu}^{TeV}$), as well as $\Delta E_\mu/\Delta L$ and ${N_\mu}^{GeV}$, are uncorrelated, thus showing that the observed effect is not connected to the shower development, but through the EAS primaries.

4. CONCLUSIONS

An analysis of cosmic ray shower primaries is performed at the Gran Sasso Laboratories by

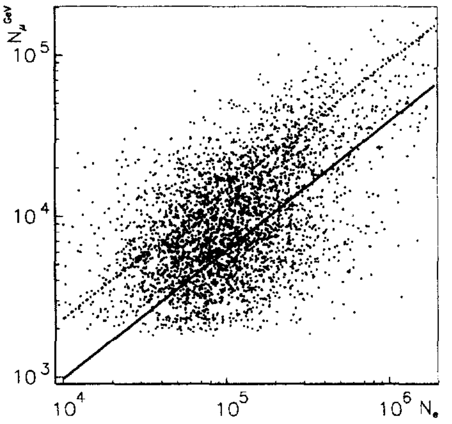

Figure 1. *Experimental N_μ^{GeV} vs. N_e data. The average predictions of the simulation for Fe (dashed) and proton primaries (solid line) are also shown.*

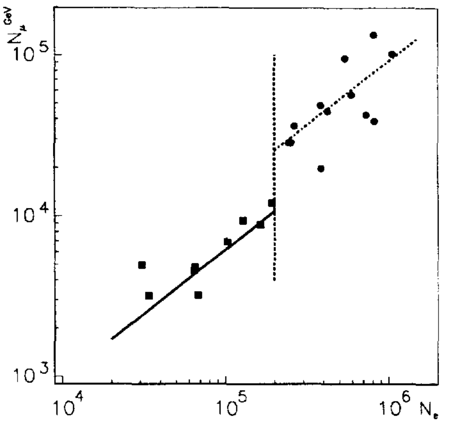

Figure 2. *N_μ^{GeV} vs. N_e for selected 'very heavy' and 'light' primaries obtained by applying cuts (a) (circles) and (b) (squares) (see text). For simulated data see fig. 1.*

the EAS-TOP and LVD experiments by using the observables Ne, $N_\mu{}^{GeV}$, $N_\mu{}^{TeV}$, and $\Delta E_\mu/\Delta L$.

The combination of the different measurements allows to select two classes of events: 'light' (proton-like) and 'very heavy' (iron-like), respectively for shower sizes $Ne < 2.10^5$ and $Ne > 2.10^5$. The events fall on clearly identified and distinct regions of the chosen parameters. Moreover they fit the expectations from the Dual Parton model of UHE hadronic interactions as implemented in the CORSIKA-HDPM code, for the two classes of primaries.

A first identification of individual cosmic ray primaries is thus obtained at Extensive Air Shower energies.

The hadronic interaction model, and the cascade code used (CORSIKA-HDPM) are on average verified.

The presence of "iron-like" primaries is proved up to primary energies $E_0 \approx 5.10^{15}$ eV.

Of course the statistics is poor, but the identification of individual events in Extensive Air Shower experiments is of utmost significance for cosmic ray measurements at high energies; the extension of the data above the *knee* of the size spectrum is now a main task.

5. REFERENCES

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