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Muon content of UHE air showers simulated with different hadronic models.

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Abstract

The longitudinal development of extensive air showers has been simulated for primary masses at fixed primary energy of 10^{14} eV with CORSIKA code using VENUS and GHEISHA codes like hadronic interaction models. The maximum development depth of electromagnetic component and the muon arrival temporal profiles have been studied. The results obtained must be confirmed simulating with other hadronic interactions models.

1 Introduction:

The mass composition study of cosmic rays has a great interest in order to obtain some information about their origin and propagation mechanisms. But for energies above 100 TeV, information about mass composition only can be obtained by indirect measurement of the extensive air showers remnants in the atmosphere, specially from their muon and electromagnetic components.

The electromagnetic component, generated by the decay of neutral pions and eta particles, increases in a great rate, reaches a maximum and decreases very quickly. The maximum development depth of this component depends on the energy and mass of the primary cosmic ray, despite of the fluctuations that affect the longitudinal development of the electromagnetic component. In the other hand muon component, generated by the decay of charged pions, does not multiply in the atmosphere, only presents ionization losses, for this reason muons in the atmosphere reach a maximum after which decrease very slowly. Muons, which reach the observation level, depends weakly on the shower development in the atmosphere and therefore information about some parameters which depend on the primary mass and primary energy can be obtained.

2 Simulation:

A Monte Carlo simulation of extensive air showers has been performed with CORSIKA (COsmic Rays SImulation for KAscade) code, version 5.62. For hadronic interactions the program invokes VENUS and GHEISHA codes above and down 100 GeV respectively. The EGS code is invoked for the electromagnetic interaction treatment. Detailed information about the program and the interaction models can be found in [1] and [2].

Atmospheric air showers of 10^{14} eV have been simulated for protons, helium, oxygen and iron nuclei as primary masses. The primary nuclei have vertical incidence ($\theta = 0$ and $\phi = 0$). The observation level has been chosen at see level (1030 gcm^{-2}), although some data of electromagnetic component at mountain altitude (810 gcm^{-2}) will be shown in next sections. The threshold energies above which the particles are detected will be specified in each section.

3 Electromagnetic longitudinal development:

The longitudinal development of the electromagnetic component has been studied for the primary energy and primary masses specified in the last section, in order to distinguish the characteristics in the electromagnetic longitudinal development produced by different primary masses for a fixed primary energy.

Tables 1 and 2 show some parameters related to the development of cascades in the atmosphere, the maximum development depth, the average shower size at detection level (1030 gcm^{-2}), at mountain altitude (810 gcm^{-2}) N_{emt} and at the maximum development depth N_{emax} ,with their respective standard deviations. The maximum development depth values are affected by a systematical error of 20 g cm^{-2} due to the bin width. The threshold energies for electron and muon detection are different for table 1 and table 2.

Table 1: Parameters of longitudinal development. The threshold energies for electrons and muons are 0.1GeV and 0.5 GeV respectively. The maximum development depth X_{max} is expressed in g cm^{-2}

	p	He	O	Fe
$N_{showers}$	100	100	100	100
X_{max}	472	419	358	309
$\sigma_{X\,max}$	159	77	42	24
N_e	1340	851	511	300
σ_{Ne}	1532	686	318	93
N_{emt}	4479	2854	1730	1098
σ_{Nemt}	3205	1624	616.3	246
N_{emax}	14620	12630	11060	10060
σ_{Nemax}	2264	1608	1052	603

Table 2: Parameters of longitudinal development. The threshold energies for electrons and muons are 0.001 GeV and 0.05 GeV respectively.The maximum development depth X_{max} is expressed in g cm^{-2}

	P	He	O	Fe
$N_{showers}$	20	20	20	20
X_{max}	498	468	407	356
$\sigma_{X\,max}$	103	76	45	24
N_e	4201	4466	2768	2005
σ_{Ne}	2997	2673	1067	670
N_{emt}	14650	16990	10220	6478
σ_{Nemt}	7283	8393	3055	1568
N_{emax}	38650	51440	43700	38900
σ_{Nemax}	5264	6387	3345	2819

Comparing the results obtained using different threshold energy for muons and electrons, the highest precision has been obtained with the lowest energy cuts, indeed some results in table 1 could not be used to obtain information due to their high fluctuations, specially those that are obtained with light nuclei, so low energy threshold must be used to obtain accurate information in cascades with light primary nuclei. Moreover studying electromagnetic component of lower energy (between 0.05 and 0.5 GeV in this case) more information about the longitudinal development can be obtained because the interactions processes with atmospheric nuclei are different at these energies.

From tables 1 and 2 it can be inferred that showers with light primary masses develop deeper in the atmosphere and with more fluctuations than showers with heavier primary masses. The fluctuations that affect our results are statistical fluctuations and intrisic fluctuations due to the shower development. Showers produced by protons and helium nuclei are more affected by fluctuations in their development due to the first interaction depth fluctuations.

Under the superposition model aproximation for the air shower development, it can be inferred that the maximum development depth verifies:

$$X_{max} = a \log(E / A) + b$$

At a fixed primary energy it can be obtained the next relation between the maximum development depth X_{max} and the decimal logarithm of the primary mass logA:

$$X_{max} = m - n \log A$$

In figure 3 the maximum development depth is plotted against primary masses and the straight lines corresponding to the linear fits for two sets of data are shown. The parameters of the two linear fits can be found in table 3.

It is found a good agreement between our values of the maximum development depths shown in table 2 and the values given in [3] for iron nuclei. The results of table 1 can not be compared because the threshold energy for electrons and muons is too low. The agreement is not as good as for proton primary showers due to the fact that this type of showers are more affected by fluctuations and more number of events should be necessary to get better accuracy.

Table 3: Linear fit parameters and their errors corresponding to the two data sets. Energy cuts for electrons and muons respectively are 0.1 GeV and 0.5 GeV for Data 1 and 0.001 GeV and 0.05 GeV for Data 2

	M	Δm	N	Δn
Data1	473	1	-94	2
Data2	506	9	-83	8

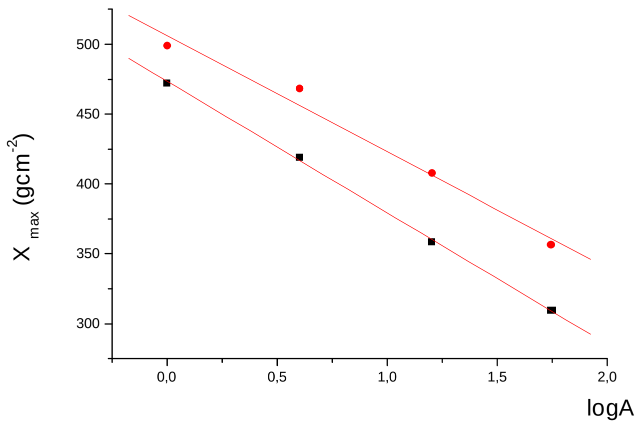

Figure 1: Maximum development depth X_{max} dependence on primary mass. Data 1 (■) and Data 2 (●).

4 Muon arrival temporal profiles:

The temporal profiles of the arriving muons at detection level have been studied for muons with above 0.5 GeV threshold energies. The origin for these temporal profiles is the first interaction time. Figure 2 shows some examples of these temporal profiles for protons, helium, oxygen and iron nuclei.

From the muon arrival temporal profiles the FWHM's have been obtained. The difficulty of the measurement of the FWHM is that the profiles are very narrow. The accuracy of these measurements is 1ns. Those profiles which have FWHM equal or minor than 3 ns have not been considered because in them the main contribution corresponds to the muons near the shower core and so information about the longitudinal development of the shower in the atmosphere can not be obtained.

Our method to measure the FWHM of the temporal profiles have been applied to a low number of events and some preliminar results of the FWHM mean and r.m.s. of the temporal profiles are shown in table 4.

Table 4: FWHM mean and r.m.s. of of the muon arriving temporal profile.

	p	He	O	Fe
$N_{showers}$	38	37	43	36
FWHM	22	21	24	25
σ_{FWHM}	16	19	18	22

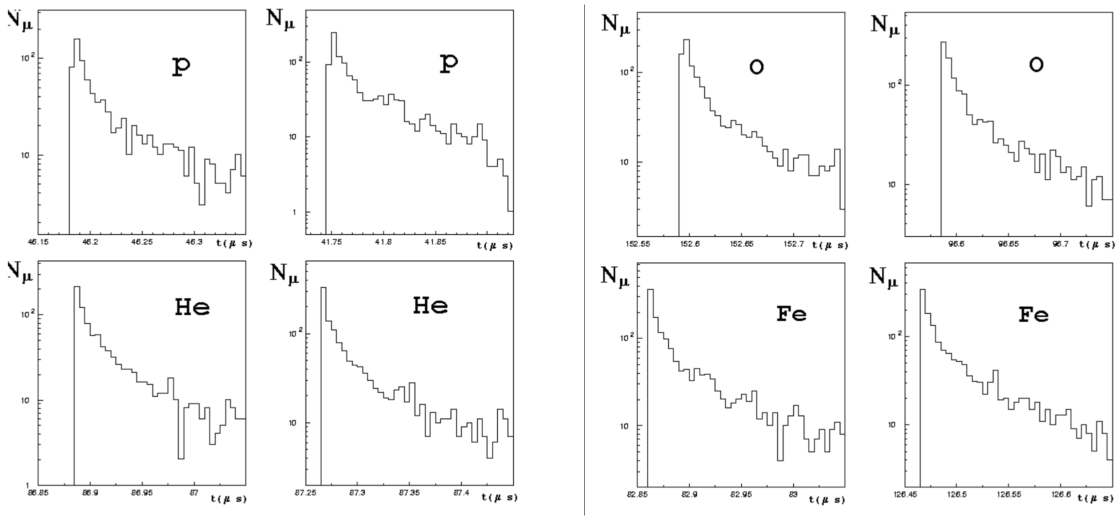

Figure 2: Muon arrival temporal profiles for protons, helium, oxygen and iron nuclei. The arrival time is expressed in μs.

It would be necessary to increase the event number to improve the accuracy of our results, but we could infer a tendency of the temporal profiles to expand increasing the primary mass, although this hypothesis must be confirmed with increasig the statistic. The interpretation of this phenomenon will be treated in future works and some information about the longitudinal development of the showers could be inferred.

5 Conclusions:

The longitudinal development of the extensive air showers in the atmosphere with 10^{14} eV primary energy has been studied for different primary masses by two methods, the maximum development depth of the electromagnetic component and the muon arrival temporal profiles.

From the longitudinal development depth it can be inferred that the cascades with lighter masses develop deeper in the atmosphere and with more fluctuations than showers with heavier primary masses. The fluctuations in longitudinal development of the light primary mass showers are mainly due to the fluctuations in the first interaction depth.

In the other hand the FWHM of the muon temporal profiles has been measured and some preliminary results of the FWHM are shown in table 4 for four primary masses. A better accuracy would be obtained with more statistic, but it could be observed an increase of the FWHM and therefore increasing the primary masses. This tendency would be confirmed increasing the number of events simulated and with other hadronic interaction models.

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