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A study of the number of muons in air showers at the detector level at energies around 1 TeV

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The relative size of the muonic component in atmospheric air showers is important to infer the composition of the primary cosmic ray and also for the gamma/hadron discrimination. Iron-initiated showers produce more muons than proton-initiated showers. However, we found that below ~1 TeV, the number of muons reaching the detector is larger for proton showers. The reason for that was that the energy of muons produced by low-energy iron showers is not large enough, and many of those muons do not live long enough to reach the detector level. This means that below ~1 TeV, the sensitivity to iron showers, in water Cherenkov detectors, is significantly reduced. This needs to be considered when calculating the cosmic ray energy spectrum at this lower energy range. In this work, we use CORSIKA simulations to quantify the size of the muonic component at the detector level for proton and iron showers as a function of shower energy and for different detector altitudes relevant for SWGO and LHAASO observatories.

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1. Introduction

Cosmic rays (CRs) are massive particles originating from outer space and account for about 1% of the total mass of the universe [1]. These cosmic rays can be detected in the Earth. In its first interaction with the atmosphere, the cosmic ray generates a shower of particles known as an extensive air shower (EAS). These EASs are composed of a wide variety of secondary particles, with the muonic component and the electromagnetic component standing out for their properties/abundance. The muonic component consists of muons and antimuons (μ^-, μ^+), while the electromagnetic component is composed of electrons, positrons, and gamma rays (e^-, e^+, γ). Studying both components offers a promising approach to determine the energy and mass composition of the primary cosmic ray, helping us differentiate between gamma ray and hadronic showers (generated by protons or any other atomic nucleus) [2]. To detect EASs, there are two detection methods: direct detection using satellites (carried onboard rockets) or balloons, and indirect detection using surface detectors such as scintillation detectors or water Cherenkov detectors [3]. Since the cosmic particle flux decreases as its energy increases, the direct detection method is not economically and technically viable for the highest energies ($E_p > 10^{13}$ eV), while the indirect method is feasible [4].

Preliminary investigations have shown an unexpected result: the number of muons reaching the detectors in showers initiated by individual protons is higher than that produced by iron nuclei at low energies of around 1 TeV or less, contrary to what is observed at higher energies. This research aims to understand the underlying reasons behind this pattern in muon deposition by conducting simulations using CORSIKA-77420. The simulations involve the study of extensive air showers (EAS) initiated by iron nuclei and protons with energies ranging from 100 GeV to 100 TeV, which falls within the energy range of LHAASO and SWGO. Cascade simulations were performed by setting the observation level at altitudes of 0, 4800, and 10000 meters above sea level to study the evolution of the showers.

2. Extensive Air Shower simulations

In this study, version 77420 of CORSIKA, updated on May 20, 2022, will be employed. The selected interaction models for low and high energies are UrQMD (Ultrarelativistic-Quantum Molecular-Dynamics) and QGSJET-II (Quark Gluon String model with JETs - II), respectively. The QGSJET-II model was specifically designed for the study of cosmic ray interactions, focusing on the analysis of ultra-high-energy cascades [7][6], while UrQMD is responsible for hadronic interactions at low and intermediate energies [8]. Given the installation altitude of SWGO, the simulations were primarily performed considering one of the proposed candidate sites in Arequipa, Peru, namely Yanque, located at an approximate altitude of 4800 meters above sea level (masl). However, in order to make additional comparisons, simulations were also conducted at sea level (0 masl) and at an altitude of 10000 masl. The energy range of the study spans from 100 GeV to 100 TeV. The simulated primary particles include iron, nitrogen, and helium nuclei, as well as protons. To improve our statistical precision, 1000 cascades were simulated per run for each energy within the aforementioned range and for each simulated particle. A thinning method was applied (detailed information on the thinning method can be found in [5][9]). The thinning factor selected during the research was $\varepsilon_{\text{th}} = 10^{-2}$.

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On the other hand, a cutoff energy of 300 KeV was set for hadrons and muons, while for electrons and gamma rays, the cutoff energy was fixed at 3 KeV. To obtain the values of the magnetic field in the Arequipa region at a height of 4800 masl, the NOAA (National Oceanic and Atmospheric Administration) web tool [10] was used, which provided us with the magnetic field values of approximately $B_x \approx 22.955$ nT and $B_z \approx -3.849$ nT, where B_x is the northward component of the Earth's magnetic field and B_z is the vertical component of this field.

2.1 The muonic component

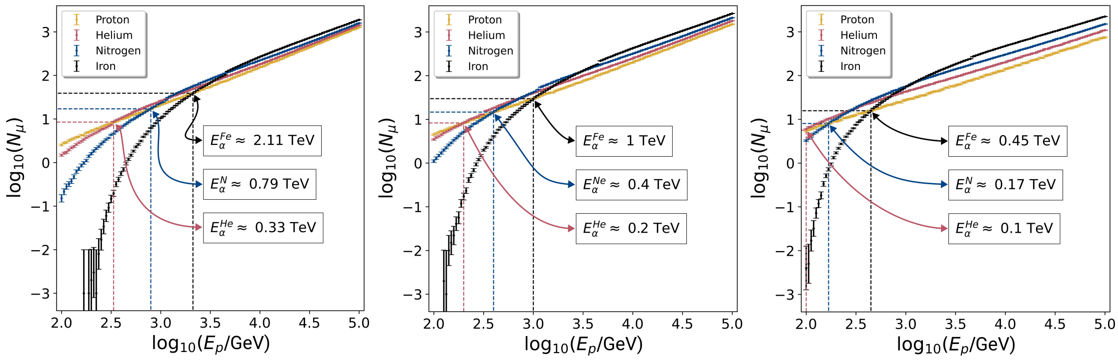
Muons are primarily produced in hadronic cascades, as they result from the decay of charged pions and kaons. The primary hadron passes through the atmosphere, when it interacts it produces charged pions. These charged pions can then interact or decay producing more muons. This process is repeated until the energies of the pions drop below a critical energy ξ_c^π, and they can only decay to muons. In addition to charged pions, neutral pions are also produced, which immediately decay into photons, resulting in electromagnetic cascades. The superposition model [11], states that an atomic nucleus made up of A nucleons should behave like individual A nucleons traveling in parallel and therefore this nucleus should produce more muons than a nucleus with fewer nucleons. An iron nucleus ($A = 56$) should produce more muons than an individual proton.

In CORSIKA, inelastic hadronic interactions of muons are omitted because they are very rare. Instead, bremsstrahlung interactions and pair production (e^-, e^+) are considered, along with muon decay according to $\mu^\pm \longrightarrow e^\pm + \nu_e + \nu_\mu$ [5]. On the other hand, muons that survive all the mentioned interactions reach the detection level with a certain energy E. This energy must be above a threshold energy E_{th} to generate Cherenkov radiation and be detected by Cherenkov water tank detectors located on the Earth's surface. For muons, this threshold energy is approximately 160 MeV.

3. Results

In this section, we will present the results of our simulations of EAS using the CORSIKA. As discussed in previous sections, our main objective is to simulate different scenarios of cascades initiated by iron nuclei and protons, primarily at an altitude of 4800 meters above sea level, within an energy range from 100 GeV to 100 TeV. However, to provide a comprehensive study, simulations were also performed at altitudes of 0 and 10000 masl. The purpose of these simulations is to explain why below a certain primary energy ($\lesssim$ 1 TeV), proton-initiated cascades deposit "more muons" than those initiated by iron nuclei at an altitude of 4800 meters above sea level. We will begin by presenting the graph that illustrates this phenomenon.

It was observed that at 0 masl in Figure 1a, when the primary energy is less than about 2.11 TeV (critical energy), proton-initiated cascades deposit a larger number of muons compared to heavier nuclei. However, as the altitude increases, such as at 4800 masl in Figure 1b, this critical energy decreases to 1 TeV. Furthermore, at an even higher altitude of 10000 masl in Figure 1c, this critical energy is even lower, approximately less than 0.45 TeV. In the region of interest (100s of GeV), the difference in the number of muons deposited in the ground is more pronounced when proton-initiated cascades are compared with iron-initiated cascades. This difference depends on energy; at much lower primary energies, the difference is almost three orders of magnitude, meaning that



(a) **(b)** **(c)**

Figure 1: Comparison of the number of muons N_μ deposited at the detection level as a function of the primary energy E_p for particles of different masses at altitudes of a) 0, b) 4800 and c) 10000 masl. Muons with energies exceeding the 300 KeV cutoff threshold were taken into account.

iron deposits 1000 times fewer muons than protons at all detection levels. Figure 1 indicates that not only iron nuclei deposit fewer muons than protons below certain energies, but, this behavior is repeated with the rest of the nuclei (nitrogen and helium) . We have found that at a height of 0 masl the critical energies (E_α) are 0.79 and 0.33 TeV for proton-nitrogen and proton-helium respectively. At 4800 masl these critical energies are 0.4 and 0.2 TeV and at 10,000 masl these energies are 0.17 and 0.1 TeV. Furthermore, it can be seen that this difference in muon deposition occurs not only when protons are compared to the heavier simulated nuclei, but also when the muon deposition of a light hadron like helium is compared to its heavier counterparts like nitrogen or iron.

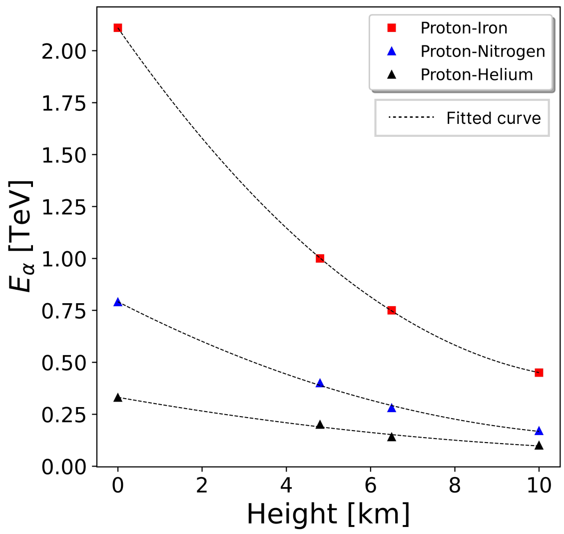


Figure 2: In this graph we observe the primary critical energy E_α as a function of detector height to which the heavy nuclei primary such as iron, nitrogen and helium begin to deposit more muons than the proton primaries.

Figure 2 shows the primary energy (E_α) from which the heaviest nuclei begin to deposit more muons than protons as a function of height. A second degree polynomial regression was carried out on the three curves:

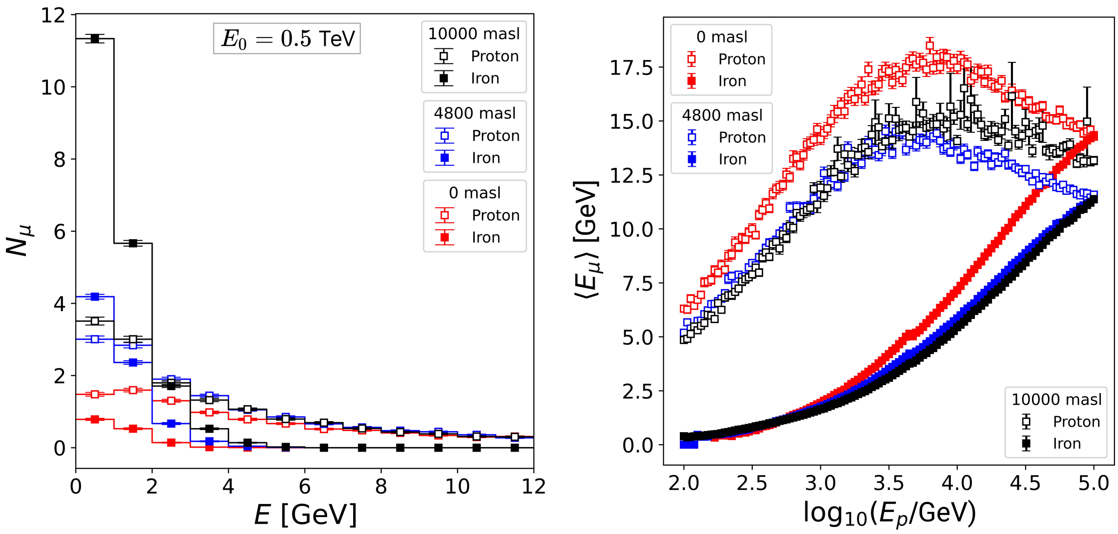
$$E_\alpha = A * Height^2 + B * Height + C \tag{1}$$

where the constants of the fits of all the curves of Figure 2 are shown in Table 1.

Particles	A $\times 10^{-2}$ TeV/km^2	B $\times 10^{-1}$ TeV/km	C TeV	R^2
Proton-Iron	1.246 ± 0.014	-2.906 ± 0.014	2.110 ± 0.003	0.999
Proton-Nitrogen	0.412 ± 0.069	-1.036 ± 0.071	0.791 ± 0.016	0.998
Proton-Helium	0.120 ± 0.069	0.354 ± 0.071	0.331 ± 0.016	0.991

Table 1: Constants of the fits of the curves of the Figure 2

Figure 2 shows that as the detection height increases, the energy E_α decreases. This is because showers initiated by lower energy nuclei, produce abundant low energy muons, lower than 2GeV (Figure 3a). These low energy muons have a larger probability of decaying before reaching ground level. The relativistic γ factor for a 2 GeV muon is only 19. Therefore, the muon decay time of 2.2 μs, gets dilated to only 41.8. Such dilated decay time allow muons to travel only around 8 km before decaying. For 1 GeV muons this distance is reduced to 4 km. Figure 3b shows that only Iron showers with energies above 5 TeV, are able to produce muons with average energies above 4 GeV (at 10km m.a.s.l.). Most of these muons reach the ground level before decaying.



(a) **(b)**

Figure 3: This figure shows comparisons of cascades initiated by protons and iron nuclei. Graph a) shows the energy distribution for protons and iron nuclei of 0.5 TeV at 4800 masl and 10000 masl. Graph b) shows a comparison between the average energy of the muons deposited by the iron nuclei and the protons at different heights.

In order to compare the number of muons in proton-initiated showers and iron nuclei at low energies (where proton showers deposit a greater number of muons at different detection heights, as shown in Figure 1), showers with primary energy of 0.5 TeV were selected. Figure 3a shows the energy distribution of the muons deposited at 0, 4800 and 10000 masl. Figure 3a clearly reveals that in general, at an altitude of 10000 masl, there are many more muons present in cascades generated by iron nuclei. However, they have lower energies (below 2 GeV) compared to the muons present in showers generated by protons at the same altitude. Therefore, as the cascades develop through the atmosphere, this difference in the number of muons decreases. Being able to appreciate that at 0 masl the amount of muons in showers generated by iron nuclei decreases in such a way that even the amount of muons generated by protons showers is greater.

Figure 3b shows a comparison of the average muon energy as function of primary energy for proton and iron initiated showers and for three observation levels 0, 4800 and 10000 masl. This figure reveals that at all observation levels, the average energy of muons in proton-initiated cascades are, on average, more energetic than those in iron-initiated cascades. This is consistent with the superposition model, where iron-initiated cascades create a larger number of lower-energy muons compared to proton-initiated cascades (as seen in Figure 3a). In Figure 3b, we also observe that at 0 msnm, the muons deposited by iron nuclei are, on average, more energetic than at 4800 msnm and 10000 msnm. This is because the less energetic muons (at higher altitudes) rapidly decay as they traverse the atmosphere, leading to an increase in average energy at lower altitudes.

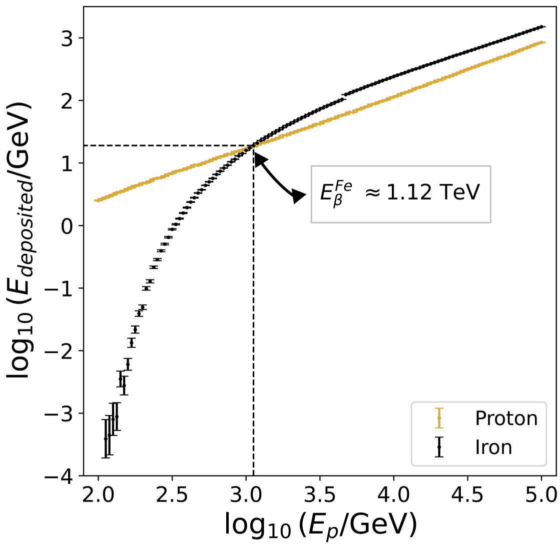


Figure 4: Energy lost by muons at a 3m height Water Cherenkov Detector (WCD) as a function of primary energy. This is for an observation level of 4800 masl. The energy lost is a proxy to signal generated in the WCD.

Analyzing exclusively one of the simulation heights (4800 masl), we saw in Figure 1 that at energies below approximately 1 TeV iron nuclei deposit fewer muons than protons. However, not all of these muons are capable of generating a signal in Cherenkov water tank detectors, because their energies fall below an energy limit of 160 MeV (minimum muon energy for Cherenkov light production in water). Figure 4 shows the maximum energy lost by muons with enough energy to produce Cherenkov radiation in thw WCD as a function of primary energy. Muons with energies below 160 MeV were ignored in this analysis. In addition, a Cherenkov tank with a height of 3 m and a muon energy loss of 2 MeV/cm was assumed. Under these conditions, it can be deduced that, regardless of the energy of the muon, they deposit a maximum of 600 MeV in the Cherenkov detectors. Figure 4 also shows that at primary energies below about 1.12 TeV, WCD at 4800 masl would detect more energy from muons generated by proton-initiated cascades than by iron nuclei. This indicates that below a certain energy threshold, the sensitivity to iron showers is significantly reduced, which must be taken into account when calculating the energy spectrum of cosmic rays in this low energy range.

4. Conclusions

We have studied in detail how the deposition of muons at the detection level is sensitive to the mass and energy of primary particles, using data obtained from simulations carried out with the CORSIKA-77410 program at initial heights of 0, 4800, and 10000 masl. For this analysis, cascades initiated by protons, iron nuclei, nitrogen, and helium were simulated within a range of primary energies from 100 GeVs to 100 TeVs.

At primary energies below 1 TeV, protons deposit more muons than heavier nuclei at an observation level of 4800 masl (Figure 1). Iron initiated showers do produce a larger number of muons. However, as suggested by the superposition model, these muons have lower energies than those produced by proton initiated showers. Therefore, in the case of low energy Iron showers, there are many low energy muons (below 2 GeV) that decay before reaching detector levels (Figure 3a). We have estimated the critical energy at which proton showers deposit more muons than Iron, Nitrogen and Helium showers as a function of the observatory altitude (Figure 2).

We have calculated that for an observatory located at 4800 masl, proton shower with energies below 1.12 TeV will produce more signal in WCDs than those from Iron initiated showers with the same energy (Figure 4).

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