Hybrid approach to the primary cosmic ray composition

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***Abstract*. In this work we discuss the advantage of combining a classical extensive air shower array with an Imaging Atmospheric Cherenkov Telescope having the ability to detect Direct Cherenkov (DC) light like H.E.S.S. experiment which derived using this technique the spectrum for cosmic iron nuclei in the energy range 50-200 TeV. Such a hybrid detector will offer a unique opportunity to test the different criteria used for the identification of primary cosmic ray particles (muon electron abundance, hadron content and lateral profiles), and then to approach the elemental composition around the knee of the primary cosmic ray energy spectrum when validated criteria are extended beyond the present DC energy window.**

***Keywords*: primary composition, IACT, hybrid detector**

I. Introduction

Cosmic rays provide important information on high energy processes occurring in our galaxy and beyond. They represent an extraterrestrial or even extragalactic matter sample whose chemical composition is expected to furnish crucial clues on their sources and the acceleration mechanism. Nevertheless, the spectrum of primary cosmic rays decreases dramatically with increasing energy so that a direct measurement of their high energy component with detectors of limited collecting power flown at the top of the atmosphere eventually runs out of statistics. Observation at energies in excess of about 10^{14} eV must therefore resort to indirect methods mainly through measurements of air showers induced in the atmosphere by primary cosmic ray particles.

However, the determination of the chemical composition of the primary cosmic rays by any indirect technique is particularly difficult. On the one hand, the interpretation of air shower parameters in terms of cosmic ray composition is hampered by our lack of knowledge of the particle interaction physics, especially at very high energy. On the other hand, air showers present very large fluctuations even if they are initiated by primary cosmic ray particles of the same mass and the same energy. Even more problematic is the fact that classic air shower experiments only sample the air shower at one depth, and then not the whole shower front but only the particles that cross the detectors. Thus extensive fitting and interpolation are needed to determine the particle content of the shower and its energy.

Recently, a novel technique for the detection of primary cosmic rays by Imaging Atmospheric Cherenkov Telescopes (IACT) has been used successfully by H.E.S.S. experiment [1]. This technique relies on the ground-based detection of the Direct Cherenkov (DC) light emitted by the primary cosmic ray particle prior to its first interaction in the atmosphere. The charge of the primary particle Z can be estimated from the intensity of this light, since it is proportional to Z^2. A very precise measurement of the energy spectrum for cosmic ray iron nuclei in the energy range 13-200 TeV has thus been achieved. However this technique can be applied only in a limited energy range depending on the charge of the primary particle. The lower limit of this energy range is determined by the Cherenkov threshold. At higher energy, the air shower Cherenkov light overwhelms the DC-light which results in an upper energy limit to this technique.

At first glance this new technique is just to be added to other direct techniques covering the same energy. Yet, on thinking it over it has a big advantage over all other techniques. Besides being the most accurate method for measuring cosmic ray composition beyond 10 TeV [1], DC-light detection can be combined with a classic air shower experiment in order to measure on an event-by-event basis the energy and mass of the primary particle and simultaneously the particle content of the shower at the observation level. Such a hybrid experiment will offer a unique opportunity to test experimentally in detail the different criteria used for the identification of primary cosmic ray particles and then to approach the elemental composition around the knee of the primary cosmic ray energy spectrum when validated criteria are extended beyond the present energy window.

II. Results and discussion

In order to examine the question in detail, we have carried out a set of Monte Carlo calculations using CORSIKA package (version 6.617) [2]. We have used two independent high energy hadronic interaction models, namely QGSJET (version II-03) [3], [4] and SYBILL (version 2.3) [5], so as to assess the systematic errors arising from the hadronic interaction modeling. At low energy (below 80 GeV), we have used FLUKA model (version 2006.3b) [6], [7]. We have considered only three types of the primary cosmic ray particle: proton (p), nitrogen (N) and iron (Fe), and two values of the primary energy: 50 and 200 TeV. The zenith angle is fixed to 0°. The observation level is set to 1830 m (830.5 g cm^{-2})

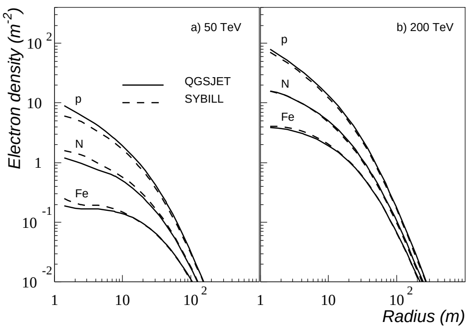

Fig. 1. Average electron lateral distribution.

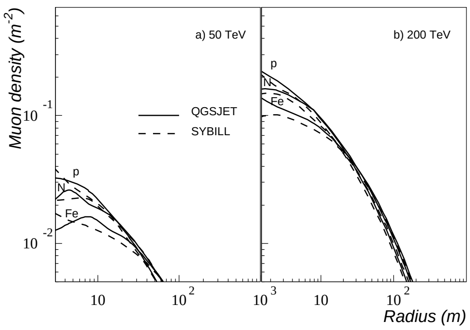

Fig. 2. Average muon lateral distribution.

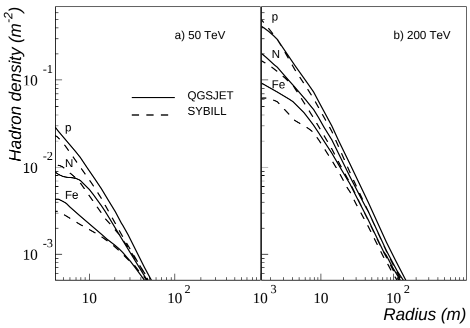

Fig. 3. Average hadron lateral distribution.

which is the altitude of H.E.S.S. experiment taken here as our IACT reference. The detection kinetic energy threshold is fixed to 2 MeV for the electrons and 300 MeV for the muons. To save computing time, we have used 100 showers per run.

Electrons and muons are the main particles measured in classic air shower experiments. The muon content gives a good measure of the primary energy because the muons are generated by the decay of pions and kaons high in the atmosphere and attenuate very slowly. At ground level, they are therefore about the same for showers of the same energy and primary nucleus independent of the stage of cascade development [8]. However, the muon measurement is technically more difficult because muons have generally low density than electrons and hence muon counters must be shielded from the more numerous electrons. They are usually measured simultaneously in order to improve discrimination of light cosmic ray nuclei from heavy ones.

Figures 1 and 2 show the lateral distributions of electrons and muons, respectively. As shown, the average electron content decreases with the mass of the primary particle. In contrast, the average muon contents for the three types of the primary particle, as mentioned before, are comparable. However, the muon density is much lower than the electron density. On the other hand, the muon density for iron is flatter than proton which makes its detection at large distance from the shower axis very difficult. Average electron and muon content increase with the primary energy. Both high energy hadronic interaction models, QGSJET and SIBYLL, give similar results. The difference between the two models is at most equal to 25%, SIBYLL in general giving less particles than QGSJET. We have also studied the average lateral distribution of hadrons (figure 3) which is comparable to that of muons.

We have also calculated the number of muons and hadrons falling inside a circle of a radius of 10 and 20 m at 200 TeV (table I). The number of particles crossing the detectors must be high enough to trigger the air shower array. As shown, at 200 TeV this is quite possible. At 50 TeV, the situation is rather difficult since the number of muons falling inside a circle of 10 and 20 m is about 10 and 20, respectively.

Figures 4a and 4b show the distributions of the electron shower size and and the muon shower size obtained at 200 TeV with the QGSJET model. As shown, the showers initiated by protons present much larger fluctuations than iron-induced showers. Moreover, the average electron size of proton-induced showers is higher than iron-induced showers whereas the situation as for the average muon size is just reversed.

We have also investigated different methods to calculate the primary energy E_0 from the EAS array data. Figure 5 shows the scatter-plot of the ratio of the primary energy to the number of electrons N_{e} ($<$ 30 m) falling inside a circle of 30 m radius in function of the ratio of the electron density at 15 m, Δe (15 m), to the muon density at 15 m, $\Delta\mu$ (15 m). The full line which is a

TABLE I

NUMBER OF PARTICLES FALLING INSIDE A CIRCLE OF A RADIUS R AROUND THE SHOWER AXIS AT 200 TEV.

a) Muons

R	10 m	20 m
p	40.0 (37.2)	105.4 (97.8)
N	38.0 (33.1)	104.7 (94.7)
Fe	29.5 (26.0)	89.1 (82.6)

b) Hadrons

R	10 m	20 m
p	38.2 (35.4)	62.8 (56.5)
N	20.7 (18.1)	37.6 (32.1)
Fe	13.0 (9.7)	25.4 (19.8)

SIBYLL values are between brackets.

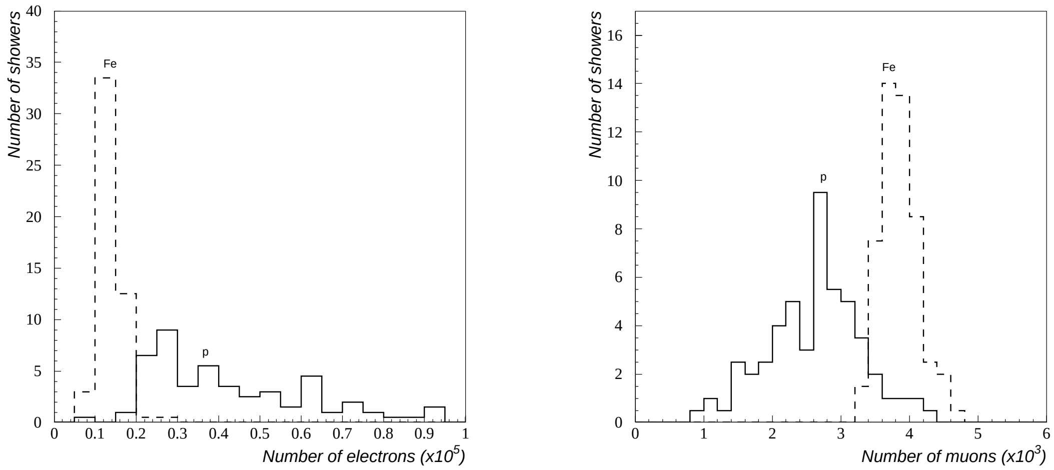

Fig. 4. Electron (a) and muon (b) distributions at 200 TeV.

simple fit to the data is given by:

$$\frac{E_0}{N\mathrm{e}(<30\,\mathrm{m})} = -15.8 + 1608.0\left[\ln\frac{\Delta\mathrm{e}(15\,\mathrm{m})}{\Delta\mu(15\,\mathrm{m})}\right]^{-2.5} \quad (1)$$

This formulation which seems to be independent of the primary mass has the advantage to reduce considerably the natural dispersion of data.

III. Conclusion

The advantage of combining a classical EAS array with an IACT able to resolve DC-light emission is discussed. Such a hybrid detector will allow to test the different criteria used for the identification of primary cosmic rays. The validated criteria will allow to approach the elemental composition around the knee of the energy spectrum of primary cosmic ray particles.

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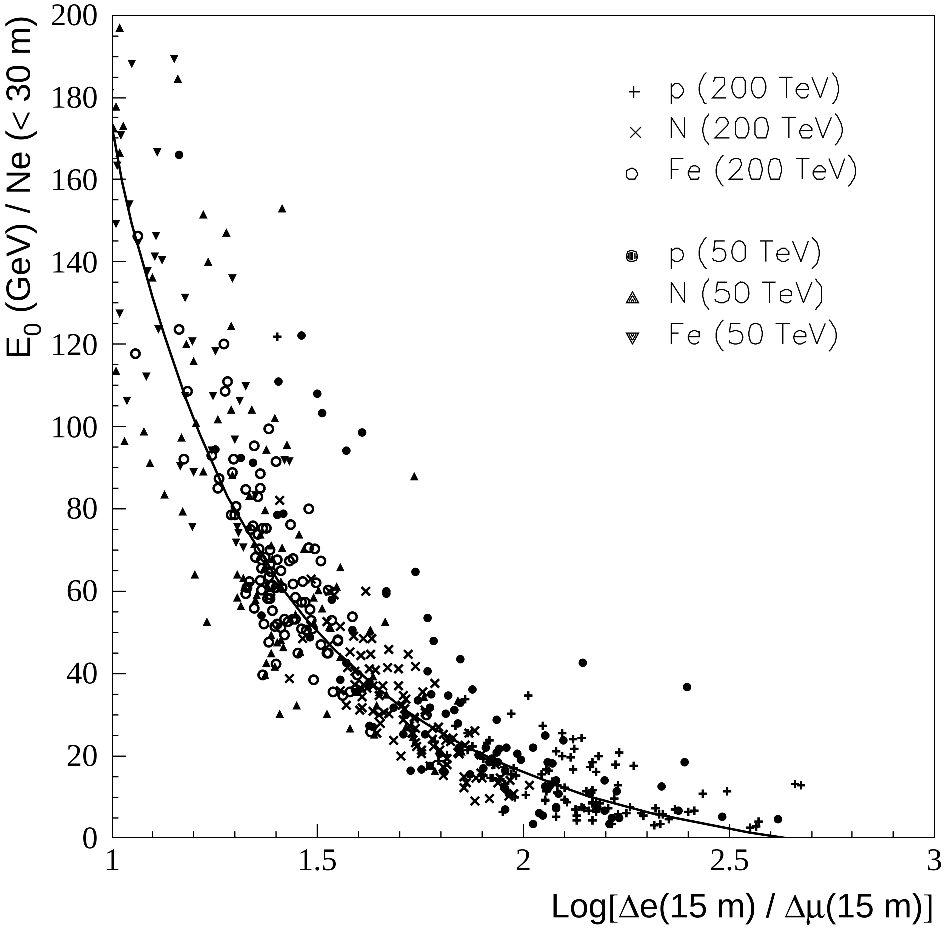

Fig. 5. Scatter-plot of the ratio of the primary energy E_0 to the number of electrons N_{e} (< 30 m) falling inside a circle of 30 m radius in function of the ratio of the electron density at 15 m, Δe (15 m), to the muon density at 15 m, $\Delta\mu$ (15 m). The full line is a simple fit to the data.