Determination of the Depth of Maximum Development and Primary Energy of Cosmic Ray Showers with AIROBICC

HEGRA COLLABORATION[1]
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Abstract

The array AIROBICC samples the Čerenkov light produced by a cosmic ray shower at core distances r < 150m. According to a detailed simulation of cosmic ray showers in the range 10 - 1000 TeV, the lateral distribution of the Čerenkov light allows us to measure the depth of maximum development with an error lower than 30 g/cm^2 and the electromagnetic energy of the shower with an error of about 7 % for 100 TeV incident particles. By using an appropiate correction based on the height of maximum development, an accurate measure of the primary hadron energy can be achieved independently of the nucleus nature. We predict an energy resolution of about 20 % at 100 TeV.

1 Introduction

The primary energy of a cosmic ray shower E_0 has been traditionally determined from the shower size N_e or/and the number of muons N_μ at observation level. These methods are not very precise because of the enormous statistical fluctuations in the development of the shower and the strong dependence of N_e and N_μ on the primary type. However, the Čerenkov light (CL) observed at ground includes contribution from all the stages of the shower development and therefore the atmosphere acts as a (non linear) calorimeter. As a consecuence, the sole measurement of CL can provide a much more accurate measure of E_0. Other methods based on the simultaneous determination of CL and N_e have been developed [1].

In this work we present the predictions of a Monte Carlo (MC) simulation about the accuracy in the determination of E_0 which can be achieved with the angle integrating Čerenkov array AIROBICC [2] at 2200m a.s.l. The development of showers initiated by γ-rays, protons and oxygen and iron nuclei with primary energy in the range of about 10 - 1000 TeV has been simulated by using the CORSIKA code [3]. A detailed detector simulation of AIROBICC has been included [4].

2 Depth of maximum development

As is well known [5], the lateral distribution of the Čerenkov light density ρ at core distances r < 110m (*hump* position) can be parametrized by using an exponential dependence on r

$$\rho = A \ \exp(-r/r_0) \tag{1}$$

where the so-called 'light radius' r_0, which is related to the slope of the lateral distribution, provides us with a good measure of the depth of maximum development X_{max}.

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For each simulated shower the position of the shower axis has been reconstructed by applying the standard algorithm employed by the HEGRA collaboration [2, 4]. As an example, in figure 1 we plot X_{max} versus r_0 for a sample of 10 degrees showers, in the energy range 10 - 1000 TeV, from which we deduce an error (σ) of about 15 g/cm^2 for gammas (assuming they could be distinguished from hadron primaries) and 30 g/cm^2 for hadrons.

3 Primary energy

3.1 Basic considerations

In this subsection we give a brief summary of the physical basis of the method, a more detailed discussion of which can be found elsewhere [6]. As is well known, the total Čerenkov light produced by a shower is in first order proportional to the total track length of the secondary electrons (contribution from heavier charged particles is negligible) and therefore it is a measure of the energy of the electromagnetic (EM) component of the shower. For a given EM energy, statistical fluctuations of the CL at observation level are mainly due to fluctuations in X_{max}. Firstly, the energy threshold for Čerenkov emission depends on the depth at which the light is emitted. On the other hand, the atmospheric absorption depends on the mass distance to the observation point. Fluctuations due to the energy carried away by the shower-tail electrons have been found to be negligible at the observation level and energy range of our experiment (10 - 1000 TeV). Finally, the detector samples the atmospheric CL in a restricted area. However, a good estimate of the non-detected light can be obtained from the slope of the lateral distribution which is a measure of X_{max} as mentioned above. Therefore, the total amount of CL with a single correction depending on r_0 should provide us with an accurate determination of the EM energy.

In hadron-initiated showers, only a fraction f_{em} of their primary energy is converted into EM particles producing CL. As is well known, f_{em} depends on the nature of the incident particle: for a given primary energy, heavy nuclei produce fewer electrons as compared with proton showers. On the other hand, the heavier is the nucleus the faster the shower develops in the atmosphere, so that the knowledge of X_{max} gives us a measure of f_{em}. Therefore it should be possible a determination of E_0 which is independent of the nature of the incident nucleus by means of a measure of the CL at observation level together with a correction depending on r_0.

3.2 Results

These ideas have been applied to the array AIROBICC by using the MC library of the HEGRA experiment [4]. In figure 2a, it is shown the distribution of the integrated Čerenkov light L_{int} ($r < 100$ m) for proton and iron showers of 100 TeV primary energy. It can be seen that the mean value is strongly dependent on the primary type. Also the distribution of proton showers is very broad and therefore it is not possible an accurate determination of E_0 by means of L_{int}.

The broadening of the L_{int} distributions are mainly due to the fluctuations in the EM energy detected by the array. For hadrons, fluctuations of f_{em} also contribute to this broadening.

The following correction to L_{int} has been applied:

$$L_{int}^{corr} = L_{int} \cdot r_0^a \tag{2}$$

For each primary particle a value of a has been found which minimizes the effect of the EM fluctuations and therefore narrows the distributions of L_{int}. This correction, which is independent of E_0, provides a very accurate measure of the primary energy of a γ-shower for which an error (σ) of about 7 % at 100 TeV is achieved. For hadrons, this correction gives a (primary dependent calibration) error of 14 % (10 %) for protons (Fe) of 100 TeV.
A primary independent determination of E_0 is possible if we measure f_{em}. This can be achieved by using r_0 again. The same function (eq. 2) has been used for this purpose. In fig. 2b it can be seen that by using an appropriate a parameter, the mean value of L_{int}^{corr} is primary independent. As a result we have found an error in the energy of hadron showers of about 20 % at 100 TeV. However the optimal value of a for an accurate measure of the EM energy do not coincide with that obtained for the primary independent measure and the L_{int}^{corr} distributions become even broader when applying the later as can be seen in fig. 2b. We have found that this correction is independent of the angle in the range 0 - 30 degrees. A similar procedure has been applied to showers with a continuous energy spectrum (10 - 1000 TeV). Fig. 3a shows L_{int} vs E_0 for several primaries and fig. 3b the result of a correction which has been optimized for a primary energy of about 100 TeV. This correction provides a nearly primary independent measure of E_0 (variation of about $\pm 8\%$ in the energy interval 100 - 200 TeV). The same procedure can be applied to other energy intervals (a rough estimate of E_0 can be obtained from the CL density at $r = 90$ m [4]). Therefore an appropriate energy dependent correction $a(E_0)$ will provide us with an accurate primary independent measure of E_0 in a wide energy range.

4 Conclusions

A method to determine accurately the primary energy of a cosmic ray shower by measuring the lateral distribution of the Čerenkov light with the array AIROBICC has been presented. An error of about 7% (at 100 Tev) for γ-showers can be achieved. A primary independent measure of a hadron shower is possible (error of about 20% at 100 TeV). This measure will be improved by using independent correction functions for the EM and hadronic component.

5 Acknowledgements

We acknowledge the authors of CORSIKA for providing us with the code. This work has been supported by the CICYT.

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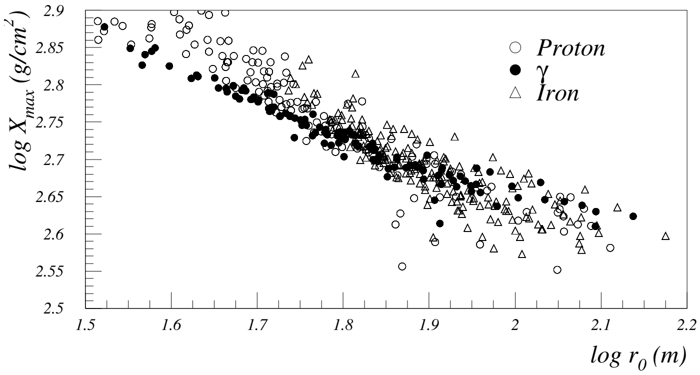

Figure 1: *log(X_{max}) vs the light radius (r_0) for γ's, protons and iron nuclei with* $10°$ *angle of incidence.*

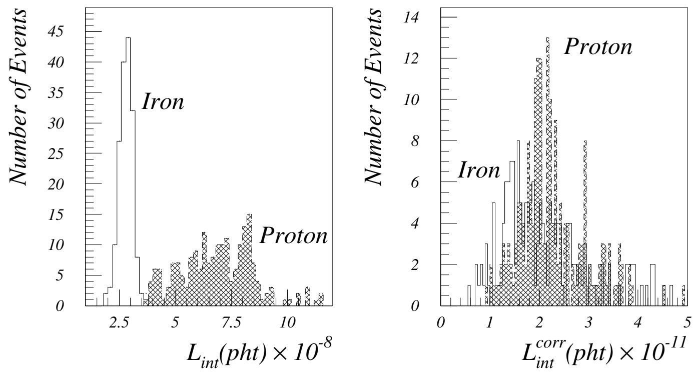

Figure 2: *Distribution of a) L_{int} and b) corrected L_{int} for cosmic showers of 100 TeV and* $10°$ *angle of incidence.*

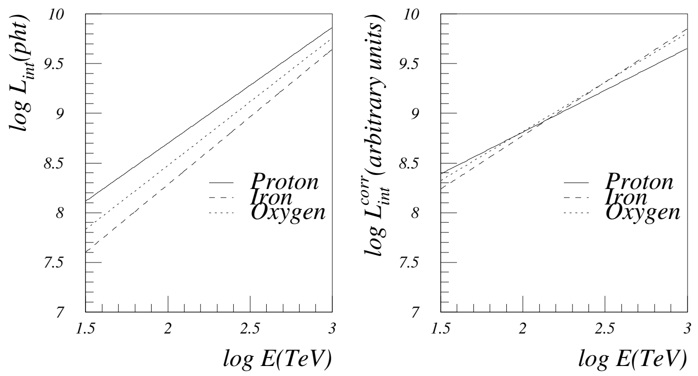

Figure 3: *a) L_{int} and b) corrected L_{int} vs primary energy, for protons, iron and oxygen nuclei with* $10°$ *angle of incidence.*