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METHODS FOR THE ENERGY DETERMINATION OF COSMIC RAY SHOWERS

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ABSTRACT

New methods for determining the energy of cosmic ray showers in the 10^{13}-10^{16} eV range are introduced. MC studies show that energy can be reconstructed regardless of primary particle nature with uncertainties ranging from 50% at 10 TeV to 10% at 10 PeV primary energy. The crucial feature of species independence makes possible a straightforward measurement of cosmic ray spectrum and provides a solid basis for chemical composition studies in this energy range.

INTRODUCTION

Experimental measurements of CR (cosmic ray) spectrum and chemical composition in the 10^{13}-10^{16} eV range are instrumental in illuminating the origin of the Knee (Hillas, 1984). It is at present controversial whether it lies on propagation or on the source mechanism itself. Even though chemical composition can provide an important clue for clarifying this issue, its value at energies around the Knee is fraught with uncertainty.

We shall outline methods for determining the primary energy E_0 of CR showers with the aid of quantities measurable in ground-based arrays of particle and Cherenkov light counters. In particular total number of electrons or Cherenkov light at hump distances, together with the position of the shower maximum X_{max}, will be shown to allow practicable measurement of E_0 independently of primary particle nature in an array like AIROBICC in HEGRA (Lindner et al., 1997a). These methods can be applied to determine CR spectrum. Furthermore such a species unbiased measure of E_0 is central when measuring CR chemical composition. Cherenkov counter matrices allow to obtain X_{max} for a given shower, a parameter which is directly correlated with primary nucleus nature. X_{max} distribution mean and width permit us to estimate the amounts of light and heavy elements in CR spectrum.

ENERGY DETERMINATION

Using the CORSIKA (Knapp and Heck, 1994) 4.068 code we have produced a library of hydrogen, helium, oxygen and iron initiated showers in the 10^{13}-10^{16} eV range. Hadronic interactions are treated with the GHEISHA (Fesefeldt, 1985) and VENUS (Werner, 1993) codes. In tracing the effects of the HEGRA particle and Cherenkov counter arrays, we performed a detailed simulation of the various detection stages (Martinez et al., 1995). An account of results assuming an ideal detector has been reported elsewhere (Cortina et al., 1997b).

Measurement of shower maximum is at the heart of our methods for determining the primary energy. A Cherenkov light counter matrix allows to determine Cherenkov lateral distribution. It is a well known fact (Patterson and Hillas 1983) that the slope of such distribution is directly related to X_{max}:

$$X_{max} = a + b \times \lambda \tag{1}$$

where a and b are parameters depending of incident zenith angle and λ is the so-called slope parameter in an exponential fit to the Cherenkov density lateral distribution:

$$\rho(r) = A \exp(-\lambda r) \tag{2}$$

This correlation has been found to be almost primary independent in the energy range of this work. In table 1, accuracies in the determination of X_{max} are tabulated for our library of hadron primaries.

Table 1: *Accuracies (σ of the distributions) in the determination on shower maximum for several hadron primary particles at 10° zenith angle.*

σ(g/cm^2)	E_0(TeV)		
primary	10^1-10^2	10^2-10^3	10^3-10^4
p	70	32	28
He	66	36	22
O	76	38	20
Fe	102	30	16

Shower size N_e and total amount of Cherenkov light at ground level have been traditionally used as energy estimators. In fact at these energies, Cherenkov light at hump distances L_{hump} is particularly accurate since it is only weakly dependent on the fluctuations of shower developement (Patterson and Hillas, 1983; Cortina et al., 1997b). Yet, both parameters suffer from a strong species dependence. Consequently they can not be employed to extract an unbiased chemical composition.

At a given primary energy, differences in L_{hump} and N_e for the various primary particles follow directly from differences in the fraction of energy which goes into the electromagnetic cascade f_{em} in the case of L_{hump}, coupled with differences in the shower development (basically in X_{max}) in the case of N_e. A smaller effect is also attributable to variations in atmospheric attenuation and Cherenkov threshold. A reasonable estimate of f_{em} can be obtained out of X_{max}. Correlation of both parameters is independent of primary particle nature. Accordingly X_{max} enables to perform a correction on L_{hump} and N_e which turns them into species independent estimators of primary energy. This is illustrated for the shower size in figure 1 where we have plotted Ne/E_0 as a function of X_{max}. Differences in Ne for a given energy are strongly correlated to the shower maximum position. (The reader should consult

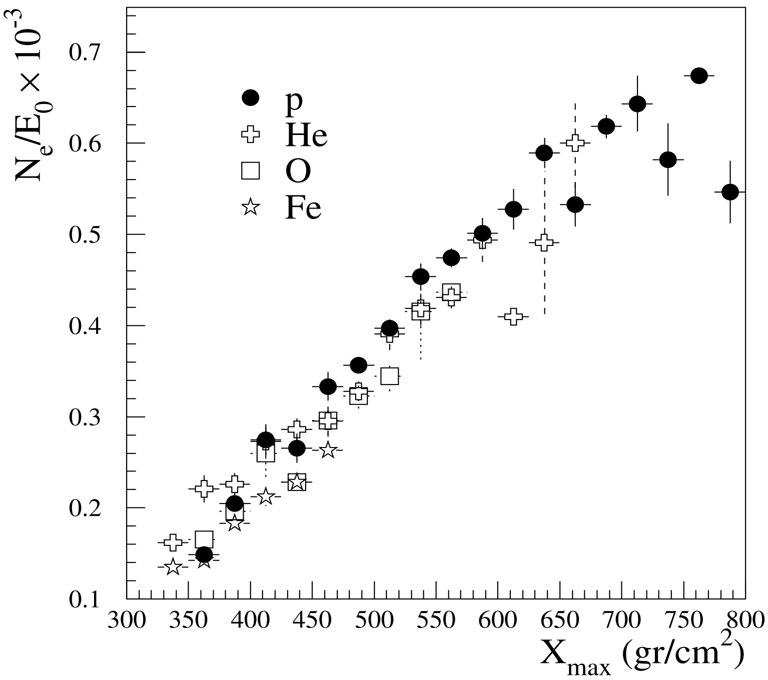

Fig. 1: Shower size upon primary energy as a function of shower maximum from several 10° hadron primaries in the 10^{14}-10^{16} eV range.

Cortina et al., 1997b, where this correction is described more fully and its physical grounds are explored. A similar method is discussed in Lindner, 1997b).

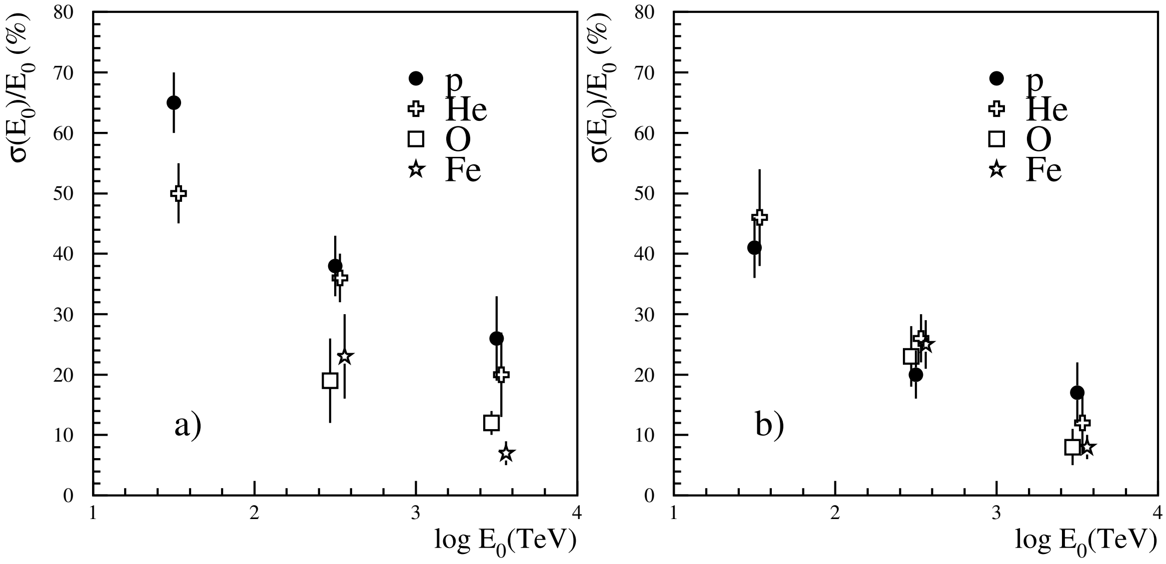

Fig. 2: Errors (σ of the distributions) in the energy determination a) from L_{hump} and b) from N_e for several hadron primary particles at 10° zenith angle

Figure 2 depicts graphically the precisions achieved in the primary energy determination. These precisions have been fitted to a law $\sigma(\mathrm{E_0})/\mathrm{E_0}=\mathrm{a}/\sqrt{E_0}+\mathrm{b}$. The first term corresponds to statistical errors whereas the second one is due to the method's systematics. Precisions smaller than 10% are attainable at energies above 1 PeV.

Table 2: *Parameters of the fit $\sigma(E_0)/E_0=b+a/\sqrt{E_0}$ for several primary particles at 10° zenith angle.*

	E_0 from L_{hump}		E_0 from N_e	
primary	a	b	a	b
p	228	24	150	13
He	146	25	203	12
O	180	4	380	1
Fe	405	0	430	0

APPLICATION TO SPECTRUM AND CHEMICAL COMPOSITION

Once methods are available to measure primary energy independently of primary particle's nature, determination of the CR all-particle spectrum is straightforward. For such measurement as performed with the HEGRA detector, we refer the reader to Cortina et al., 1997a.

Determination of E_0 can be supplemented be the information on X_{max} in an attempt to measure chemical composition (see Wdowczyk, 1994 for a review of these methods). Experimentally measured X_{max} distribution at a given energy can be compared with those determined by MC simulation. Its width and absolute position as well as the elongation rate over a whole energy range provide an estimate of CR chemistry. (elongation rate has been found to be approximately 88 g/cm^2 for all the MC simulated hadron primaries so a flatter elongation rate for measured data would indicate a transition from light to heavy composition). Nonetheless MC simulations exhibit important discrepancies at energies around the Knee (see a recent work by Knapp et al (1996) for a comparison of a number of hadronic interaction models). We have checked that an error in X_{max} of 20 g/cm^2 (as expected for extreme MC models in Knapp et al, 1996) results in a variation on the ratio of light to heavy elements at the order of 0.2. Such a ratio and some other observables have been employed to measure chemical composition in the 10^{14}-10^{16} eV range with the HEGRA array (see Cortina et al, 1997a, for an account of results).

CONCLUSIONS

Two new procedures for determining the energy of CR showers have been introduced. E_0 can be determined in a primary independent fashion in the 10^{13}-10^{16} eV range. Notwithstanding the difficulties of accurately predicting by MC methods some crucial observables like X_{max}, these method help enhance CR spectrum measurements and enable to determine CR chemical composition in this energy region.

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