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New possibilities for the Chacaltaya array(*)

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Summary. — This document presents some possibilities which could be applied to the new Chacaltaya experiment mainly on the calibration of this experiment on the ground with direct measurements from satellites or balloons, to select showers generated by primaries with different masses but with the same energy, to obtain an unbiased determination of the primary mass composition around the knee for given energies and to select gamma showers for very high energies.

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1. – Introduction

Because of the huge decrease of the cosmic radiation energy spectrum, for energies larger than 10^5 GeV, only indirect observations can be used. At the present time, the knowledge of this radiation is relatively poor. One of the best examples is that even a basic question like the mass composition is still without a definite answer. The complex situation is mainly because of two reasons:

– Cosmic projectiles generate particle showers in the earth's atmosphere. All experiments (except Chacaltaya and Tibet) analyze showers at altitudes smaller than 3200 m a.s.l. This means that showers are in their absorption phase with very large fluctuations in all the components. It is well known that the larger the fluctuations the smaller the precision of the obtained results.

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– The second reason is that the information which needs to be obtained (for example, mass and energy of the primary) is very diluted inside the hundreds of thousands of particles composing showers. This means that by trying to extract some information from the experimental data, many biases are surely included. That is why it is very important to calibrate the indirect methods with the corresponding direct results obtained by satellites or balloon-based experiments. At the present time this never has been made.

The best way to decrease the two previous handicaps is to perform EAS experiments at very high altitudes for the following three reasons:

– Showers are close to their maximum development. So, fluctuation of parameters will be minimum.

– It is possible to take into account the showers with lower energies overlapping direct results obtained by the satellites or balloon-based experiments.

– It is possible to select showers generated by primaries with different masses, but with the same primary energy.

The next pages present some synthesis of different works made for the present Chacaltaya array. Of course this is only a tool for the future. For example, all the simulated present results are for detectors with an energy threshold of 5 GeV. To be applied to the detectors used in HEGRA, energy thresholds have to be modified. In another way, all simulations have been made using a three-dimensional interaction model SM1 [1, 2]. In the future, it would be better to use the well-known CORSIKA code [3], for the Chacaltaya altitude. A good agreement has been found between the corresponding simulated results obtained using SM1 or CORSIKA at depths of 700 $\mathrm{g\,cm^{-2}}$ [4]. Preliminary attemps have shown that it is also true for 550 $\mathrm{g\,cm^{-2}}$.

2. – Calibration between direct (satellites) and indirect (EAS) measurements

The energies of primary cosmic particles are distributed inside an extremely wide interval of 10–10^{11} GeV. The corresponding energy spectrum decreases rapidly with the particle energy. Therefore, the flux intensities for energies larger than 10^5 GeV become relatively low, which limits the possibilities for their direct measurements, carried out with the help of the spectrometer apparatus on satellites and balloons. In this context the role of indirect methods for the primary energy spectrum and mass composition determinations increases and for energies of $E_0 \geq 10^6$ GeV the EAS becomes the main source of their information.

All the basic experimental results for the mass composition and the energy spectra of the primary cosmic flux obtained recently by different direct observations and measurements does not exceed the energy 10^5 GeV. Moreover, the statistical and systematical accuracies of the estimations decrease rapidly in the energy interval 10^4–10^5 GeV. At the same time, the results of the corresponding indirect experiments, based mainly on the EAS characteristic analysis, are devoted to the energy region above the 10^6 GeV band and are usually carried out at observation levels lower than 700 $\mathrm{g\,cm^{-2}}$ where the absorption of the shower particles in the atmosphere increases and where fluctuations become more essential.

However, the quantitative study of the nature of the mass composition and energy spectra using EAS indirect methods requires a careful calibration with the corresponding direct experimental results. In this case, the importance and the topicality of the EAS experiments carried out at extreme high mountain altitudes (~ 5000 m a.s.l.) increases

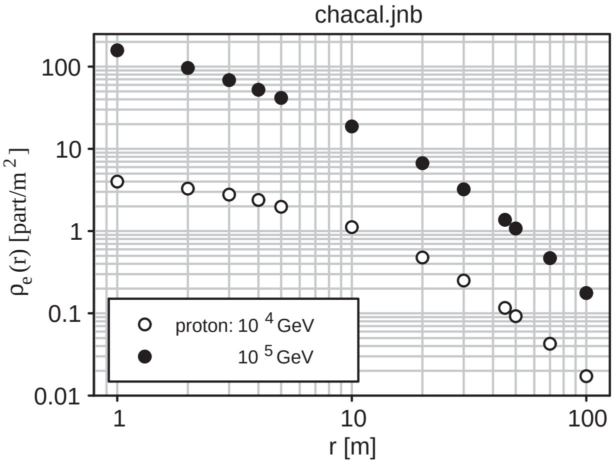

Fig. 1. – Lateral distribution of charged particles in proton showers at Chacaltaya depth.

essentially. Indeed, for such altitudes, it must be possible to observe EAS in the energy range of 10^4–10^5 GeV and to compare results with the corresponding data given directly by satellites or balloons. This possibility is with a basic importance because, up to now, never EAS data has never been calibrated with the direct measurements. As an example, the lateral distributions of charge particles are shown in fig. 1 and it can bee seen that the low energy primaries would be observable.

3. – Selection of showers with given energies

Because of the quite different development of EAS initiated in the atmosphere by primaries with different masses, it is obvious that the usual shower selection ($N_e = \text{const}$) involves biases in the energy determination of the primaries. Indeed, showers with the same size are generated by primary protons with smaller energy than heavy nuclei. So the energy determination of the primaries can only be obtained through the relation *size* ↔ *energy* which is not at all well determined. Taking this into account, it is necessary to define a new parameter such as showers selected with fixed values of this parameter which would be generated by primaries with different masses, but with the same primary energy. For the Chacaltaya experiment, this parameter has been proposed as [5]: $\alpha_e(35) = \dfrac{35^2\rho_e(35)}{\sqrt{f_{\text{NKG}}(10, S_{6\text{–}70})}}$, where $\rho_e(35)$ is the density of charged particles measured at 35 m from the shower axis, $f_{\text{NKG}}(10, S_{6\text{–}70})$ is the Nishimura-Kamata-Greisen function estimated at 10 m and $S_{6\text{–}70}$ is the measured local age parameter determined from $\rho_e(6\ \text{m})$ and $\rho_e(70\ \text{m})$. Indeed, in the energy interval 10^4–10^5 GeV, the lateral distribution of $\langle\alpha_e(r)\rangle$ shows for primary protons and iron nuclei, a crossing point close to 35 m as shown in fig. 2a. In fig. 2b, we have drawn the relative standard deviation, $\frac{\sigma(\alpha_e(r))}{\langle\alpha_e(r)\rangle}$, for different distances from the shower axis and for primaries with energy of 10^5 GeV. The dependence of the primary energy on the selection parameter $\alpha_e(35)$ for the observation level of 550 $\text{g}\,\text{cm}^{-2}$ and initiating primary protons and iron nuclei is shown in fig. 3. It is clearly seen that the shower selection with $\alpha_e(35) = \text{const}$ leads to collect events with the same primary energy E_0, independently of the atomic mass A of the ini-

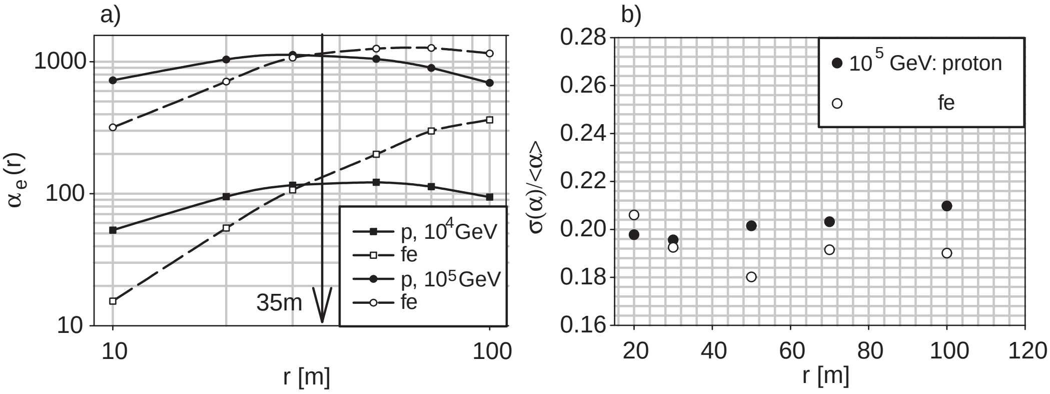

Fig. 2. – a) α_e and b) its relative standard deviation *vs.* the distance from the shower axis.

tiating particles. The estimated accuracies are limited both by the shower development, $[\frac{\sigma(\alpha_e)}{\langle\alpha_e\rangle}]_{\rm dev}$, and by the experimental "noise", $\left[\frac{\sigma(\alpha_e)}{\langle\alpha_e\rangle}\right]_{\rm rec}$. On the one side, $\left[\frac{\sigma(\alpha_e)}{\langle\alpha_e\rangle}\right]_{\rm dev}$, at 35 m from the shower axis, remains limited (smaller than 20% for all primaries). On the other side, $\left[\frac{\sigma(\alpha_e)}{\langle\alpha_e\rangle}\right]_{\rm rec}$ increases the value of the total fluctuation, $\left[\frac{\sigma(\alpha_e)}{\langle\alpha_e\rangle}\right]_{\rm total}$, according to $\left[\frac{\sigma(\alpha_e)}{\langle\alpha_e\rangle}\right]^2_{\rm total} = \left[\frac{\sigma(\alpha_e)}{\langle\alpha_e\rangle}\right]^2_{\rm dev} + \left[\frac{\sigma(\alpha_e)}{\langle\alpha_e\rangle}\right]^2_{\rm rec}$. Adopting a realistic energy dependence, $\left[\frac{\sigma(\alpha_e)}{\langle\alpha_e\rangle}\right]_{\rm rec} = f(E_0)$, where $f(10^4\ \text{GeV}) = 0.20$ and $f(10^5\ \text{GeV}) = 0.10$, the average primary energy values $\langle E_0\rangle$ could be estimated with uncertainties $\sigma(\frac{E_0}{\langle E_0\rangle}) \in [0.28, 0.1]$ in the energy interval $4\cdot 10^4$–$4\cdot 10^5$ GeV for EAS selected with $\alpha_e = \text{const}$ at an observation level of 550 $\text{g}\,\text{cm}^{-2}$.

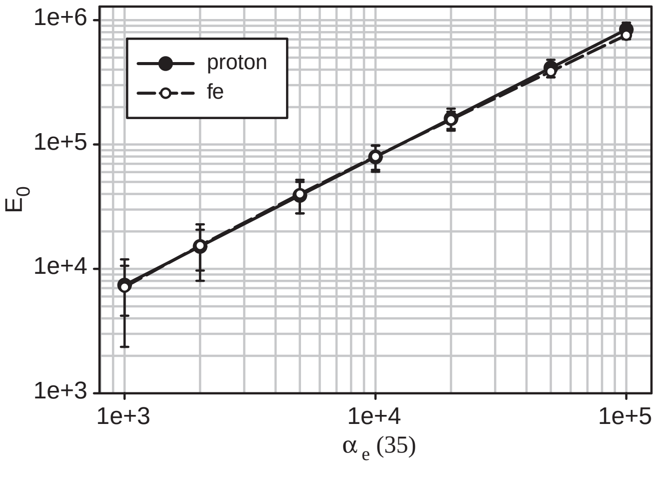

Fig. 3. – Dependence and error of the primary energy E_0 *vs.* $\alpha_e(35)$.

TABLE I. – *Values of* E_h/E_e *and the corresponding standard duration (see text for further details).*

$E_0 = 5 \cdot 10^5$ GeV	E_h/E_e	$\sigma(E_h/E_e)$	$E_0 = 5 \cdot 10^6$ GeV	E_h/E_e	$\sigma(E_h/E_e)$
p	0.306	0.123	p	0.282	0.121
Fe	0.496	0.100	Fe	0.496	0.100

4. – Unbiased determination of the primary energy spectrum

Taking into account the previous section, it becomes clear that selecting EAS with a constant value of $\alpha_e(35)$ at the Chacaltaya observation level, we could obtain the corresponding shower spectra $\frac{\mathrm{d}f(\alpha_e)}{\mathrm{d}\alpha_e}$ and, in this way, estimate the primary energy spectrum $\frac{\mathrm{d}f(E_0)}{\mathrm{d}E_0}$.

5. – Unbiased determination of the primary mass composition

Because of the possibility to select showers generated by primaries with the same energy, independently of their mass, the new Chacaltaya array will allow the estimation of mass composition for given energies. As has been underlined in the introduction, such determination is an advance because the composition will be estimated by not using the connection *size* ↔ *energy*. For the present project of the new Chacaltaya array, a calorimeter could be built and it is well known that the EAS hadron number is sensible to the primary mass. As an example, we have taken into account a calorimeter with an energy threshold of 0.6 GeV. Table I shows the values of E_h/E_e and the corresponding standard deviation where E_h and E_e are, respectively, the energies of hadrons and electrons hitting in a circled calorimeter with a radius of 5 m. It can be seen that the E_h/E_e distributions in showers generated by primary protons or iron nuclei are well separated for a large primary energy range. So, the primary mass could be determined by fitting the experimental distribution of E_h/E_e with the simulated data.

6. – Selection of gamma showers with energies of around 10^5 GeV

Many new experiments using the Cherenkov light analysis are devoted to the observation of cosmic photons in the energy interval 50 GeV–10 TeV. Indeed, the observation of neutral primaries is the only way for the location of point sources in the Universe. But, because of the limited energy range of the Cherenkov techniques, the problem of cosmic ray sources for larger energies remains open. In the past, only the Tien Shan group determined quantitatively, in EAS, that some thresholds about the muon numbers and the energy of hadrons in shower core, such as showers with muons and hadrons lower than these thresholds were claimed to be gamma showers. It must be interesting to determine, for the Chacaltaya array, some criteria based on the abnormal poorness of the hadron number in showers to be able to select gamma showers with energy larger than 10 TeV.

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