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Cosmic Ray Energy Measurement with EAS Cherenkov Light: Experiment QUEST and CORSIKA Simulation

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A new method of a primary cosmic particle energy measurement with the extensive air shower (EAS) technique has been developed by exploiting: a) the joint analysis of the shower size, obtained by the EAS-TOP array, and of the EAS Cherenkov light lateral distribution (LDF), obtained by the QUEST array, and b) simulations based on the CORSIKA code. The method is based on the strict correlation between the size/energy ratio and the steepness of the Cherenkov light lateral distribution and has been compared with a "classical" one based on the Cherenkov light flux at a fixed distance (175 m) from the EAS core. The independence of the energy measurement both on the mass of primary particle and the hadronic interaction model used for the analysis is shown. Based on this approach the experimental integral intensity of cosmic rays flux with energy more than $3 \cdot 10^{15}$ eV is obtained with good systematic and statistical accuracy.

1. Experiment QUEST and Simulations

The QUEST experiment was developed to combine wide-angle atmospheric Cherenkov light measurements with the charged particle EAS-TOP measurements (Gran Sasso, Italy, 2000 m a.s.l.)[1]. The wide-angle Cherenkov light detector was based upon five QUASAR-370 (37 cm diameter) hemispheric photomultiplier tubes installed on five telescopes (average pointing at direction $\theta = 34°$, $\varphi = 167°$).

The size N_e and core position for every shower has been extracted from EAS-TOP data. The reconstructed Cherenkov light lateral distribution function (CLDF) has been obtained from the Cherenkov light flux measured by each detector at the known distance from the axis. A new fitting function, suggested by us in ref. [1], has been used to derive two main parameters of the EAS CLDF for every recorded event: the light flux at core distance of 175 m Q_{175} and the LDF steepness, defined as the ratio of the fluxes at 100 and 200 m from the axis: $P = Q(100)/Q(200)$.

The energy measurement methods are based on analysis of artificial showers data, simulated with CORSIKA code[2, 3]. The total sample of 400 events was simulated for primary energy $1, 2, 4$ and 8 PeV, and zenith angles θ from 24° to 39°, 180 of them for primary protons and 180 for iron nuclei using QGSJET[4] model of hadron interaction and 20 for protons and 20 for iron using SIBYLL[5] model. To derive in the analysis of simulation the EAS size $N_e$comparable to the experimental one, we have taken into account both electrons and muons and used the experimental procedure of size reconstruction with NKG fitting function.

We obtained from these simulated data the dependences:

1. of the mean depth of EAS maximum X_{max} on energy E_0, shape and standard deviation of X_{max} distribution separately for p and Fe primaries,
2. of P on the linear distance to EAS maximum H_{max} and standard deviation of the P distribution for fixed H_{max},separately for p and Fe,
3. of the size N_e on P and E_0 and the standard deviation of the N_e distribution for fixed P for p and Fe,

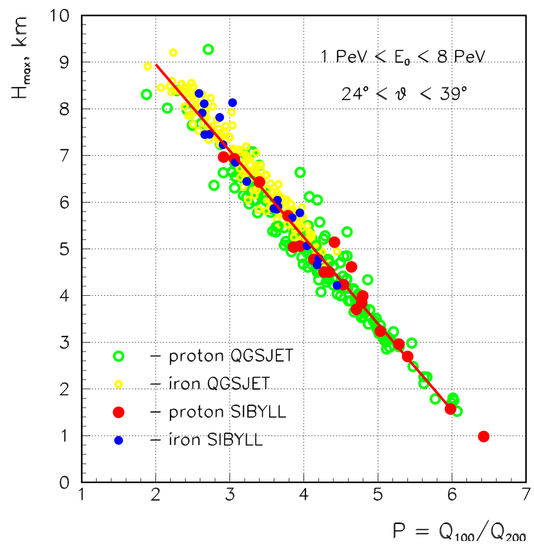

Figure 1. CORSIKA: Correlation between EAS Cherenkov LDF steepness P and H_{max}.

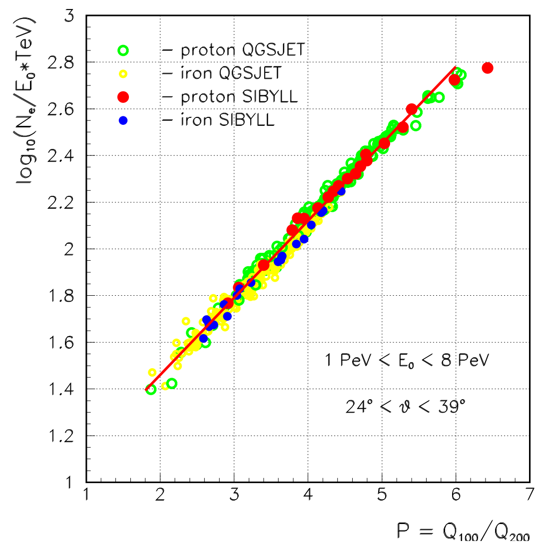

Figure 2. CORSIKA: Correlation between EAS Cherenkov LDF steepness P and N_e/E_0.

4. of Q_{175} on E_0 and the standard deviation of the Q_{175} distribution at a fixed E_0 separately for p and Fe.

Using all these parametrizations and generating as base independent parameters: the primary energy E_0 distributed as a power law spectrum, the depth of EAS maximum $X_{\max}$ distributed as an asymmetric Γ-distribution, the shower axis direction and core position we generate and analyse hundreds thousands of artificial events. Experimental errors in core position and N_e are inserted in this procedure in accordance with [6]. The real array geometry and fluctuations of every Cherenkov light detector response are taken into account. We call the described procedure "model of experiment". It is used for analysis of experimental errors, efficiency and distributions of measured parameters for different assumptions on primary composition.

To analyze the experimental data we use different parametrisations of CORSIKA simulation for complex initial composition. Figure 1 shows the connection of LDF steepness P with liner distance to EAS maximum H_{max} in [km]. The best parametrisation of this dependence is: $H_{max} = 12.65 - 1.85P$, with standard deviation of H_{max} distribution for fixed P: $\sigma(H_{max}) = 0.3km$, - which may characterize the theoretical accuracy of the method.

2. SIZE/CLDF Method: Size and Cherenkov Light LDF Steepness P

Figure 2 shows the CORSIKA simulated correlation between the CLDF steepness P and the ratio of the size to primary energy (N_e/E_0) for the 400 above described events. One can notice from fig. 1 and 2 that such relation is almost independent on parameters: primary energy, zenith angle, sort of particle and hadron interaction model. The correlation between N_e/E_0 and P is more strict than the one between N_e/E_0 and position of EAS maximum.

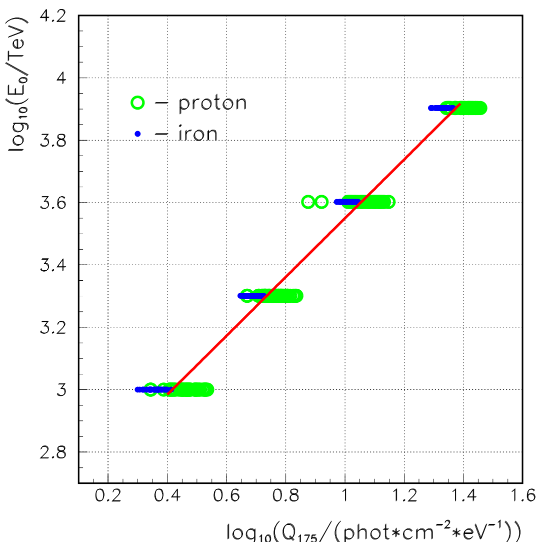

Figure 3. CORSIKA: Energy measurement by Q_{175}

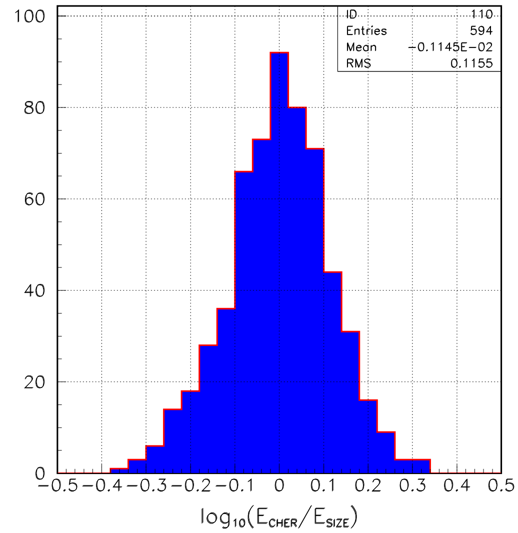

Figure 4. EXPERIMENT: Comparison of energy, obtained with two different methods for $E_{CHER} \geq 3 \times 10^{15}$ eV.

The difference between N_e/E_0 for p and Fe primaries is less than 6% and for the two interaction models less than 2% (for P=4). Using the correlation shown in fig.2 we can get the primary energy in experiment from the measurement of N_e and P:

$$E_{SIZE}\ [\text{eV}] = 1.59 \times 10^{11}\ N_e/exp(0.76P) \tag{1}$$

The main practical advantage of this method relies in the well developed technique of scintillator response calibration based on the measurement of the single particle response[6]. However the "model of experiment", described above, gives an error of individual measurement of about 35% ($\sigma(log_{10}(E_{SIZE}/E_0)) = 0.129$) mostly due to the experimental error of parameter P.

Similar method of energy reconstruction, but for LDF steepness, estimated at smaller distances from the core ($20 - 100$ m), was suggested in Ref. [7].

3. Q_{175} Method: Cherenkov Light Flux at 175 m Core Distance

Figure. 3 shows the CORSIKA simulated correlation between the primary energy and the parameter Q_{175}. Taking into account the distribution of the 400 points shown in fig. 3 we derive out an almost proportional relation between E_0 and Q_{175}: $E_{CHER} = C \cdot Q_{175}^{0.94}$.

The main problem of this "classical" method, used in many works, is in the absolute calibration coefficient C, if one includes the systematic uncertainty of Q_{175} in it. The error of absolute calibration has been estimated from 18% to 30% for different experiments. To get better accuracy we suggest to use the mean experimental ratio $< E_{SIZE}/Q_{175}^{0.94} >$, as the coefficient for the absolute calibration of Cherenkov array response. So finally:

$$E_{CHER} =< E_{SIZE}/Q_{175}^{0.94} > \cdot Q_{175}^{0.94} \tag{2}$$

”Model of experiment” displays an experimental uncertainty about 15% for the energy measurement by such expression 2, i.e. the accuracy of every individual energy measurement is much better than for the SIZE/CLDF method.

The final comparison of experimental energy obtained with two methods is shown in fig. 4. The standard deviation of the experimental distribution is very close to that obtained with the ”model of experiment” for the SIZE/CLDF method, that confirms indirectly the experimental errors estimation of the ”model of experiment”.

4. A Reference Integral Cosmic Rays Intensity

The energy measured with the Cerenkov light flux method is used for estimation of the integral intensity of cosmic rays, since the experimental error of this method for individual event is at least 2 times smaller than that for the SIZE/CLDF method. The systematic uncertainty in the definition of the integral intensity is mainly due to the estimation of the threshold energy. The main contribution to it is the uncertainty in the size N_e, which is evaluated as less than 6% [6].This leads to an uncertainty of about 12% in the integral intensity.

The maximum systematic shift of calibration coefficient, connected with the lack of knowledge of the real mass composition, was estimated with ”model of experiment” assuming pure proton and pure iron compositions. The maximum error of about 8% is obtained for primary protons. We may estimate the maximum possible systematic uncertainty as a root mean square of the sum of squares of these two values.

To analyze the experimental data we used the events with reconstructed core positions inside the effective area of 100×100 m^2 in the center of EAS-TOP array, zenith angles less than 40° and relative angles of the axis to the Cherenkov average array pointing less than 34°. 100% efficiency for such events is reached at $2.5 \cdot 10^{15}$ eV, as obtained with the ”model of experiment”.

594 events have been recorded during 140 h of data taking with energy larger than 3×10^{15} eV. The corresponding integral intensity is

$$I\left(E_0 \geq 3 \times 10^{15}\ \mathrm{eV}\right) = (2.3 \pm 0.1^{stat} \pm 0.4^{syst}) \times 10^{-7}, [\mathrm{m}^{-2} \cdot \mathrm{s}^{-1} \cdot \mathrm{ster}^{-1}].$$

A practical estimation of the stability of the integral intensity was obtained by dividing the whole statistics into two parts, one of them acquired during summer and autumn and another acquired during winter and early spring. The natural conditions of the experiment were quite different, but the difference in estimation of the reference integral intensity is 8% only, consistent with the possible statistical error.

The obtained integral intensity can be used as a reference point for other cosmic ray experiments having no precise absolute calibration.

References

[1] E. E. Korosteleva, L. A. Kuzmichev, V. V. Prosin and the EAS-TOP Collaboration, 28th ICRC, Tsukuba (2003) 1, 89.
[2] D. Heck et al., FZKA report 6019 (1998).
[3] S. Martinez et al., Nucl. Instr. & Meth. A 357, 567 (1995).
[4] N. N. Kalmykov et al., Nucl. Phys. B (Proc. Suppl.) 52B, 17 (1997).
[5] R. Engel et al., 26th ICRC, Salt Lake City (1999) 1, 415.
[6] M. Aglietta et al. (EAS-TOP Collaboration), Astropart.Phys. 10, 1 (1999).
[7] A. Lindner, Astropart. Phys. 8, 235 (1998).