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Measurement of Cosmic Ray Primary Energy with the Atmospheric Cherenkov Light Technique in Extensive Air Showers

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The advantage and problems of the primary energy measurement using the Cherenkov light from extensive air showers are discussed. The problem of absolute energy calibration has been solved during the analysis of the data of complex QUEST experiment at the EAS-TOP array. The results of QUEST experiment has been used for the analysis of the data of pure Cherenkov light array Tunka.

1. Introduction

One of the the most informative methods of cosmic ray studies is the registration of Cherenkov light from extensive air showers (EAS). The uncertainty of primary energy reconstruction becomes less if the Earth atmosphere is used as a huge calorimeter. This is possible by recording the optical radiation from EAS during clear moonless nights. The atmosphere, in the absence of clouds and aerosols, is remarkably transparent for visible light. Molecular scattering leads to losses of only 15% of light crossing the full depth of the atmosphere. But to realize all the advantages of Cherenkov light study one has to solve some specific problems of this method. The most essential is the problem of precise energy calibration of the measurements.

2. The problem of calibration of detectors

The primary energy has been estimated in classical EAS experiments by recalculation from the number of charged particles (mostly electrons and positrons). The most popular detectors of relativistic charged particles were the thin enough (2 - 5 cm) scintillators. The problem of detector calibration was solved by measuring the mean amplitude produced at the detector output by the single vertical muon. The number of particles crossed the detector is obtained as the ratio of the total output amplitute recorded at the EAS event to this calibration level. The total number of charged particles (EAS size) is reconstructed (together with EAS core position) by fitting of measured particle densities with the NKG lateral distribution function. Taking into account small photon component addition to the total amplitude and some technical corrections, the possible absolute uncertainty of the calibration was reduced to less than 6% [1].

The primary energy is proportional to the total number of particles, integrated over the total depth of the atmosphere. Taking into account the well established fact that the shape of the cascade curve almost don't vary in the wide range of variation of energy and sort of primary nuclei ([2], [14]) one may conclude that primary energy is proportional to the number of particles in the maximum of EAS longitudinal development. But estimation of energy using the measured number of particles deep in the atmosphere far from the maximum leads to the uncertainty caused by the lack of knowlege of real individual depth of maximum. It can lead to the relative error of about $\sim 50\%$.

To reduce these uncertainties the method was improved in some experiments by lifting the experimental array to the mountain level (i.e. EAS-TOP [1], Tibet [3]) or using additional information from other EAS components such as muon

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number (KASCADE [4]).

Cherenkov light measurement removes this problem, integrating light from all the atmosphere depth. This provides the relative error of energy measurement (energy resolution) $\sim$ 15% [5]. But the new problem arises in the EAS Cherenkov light experiments. It is a problem of detectors calibration.

The problem of Cherenkov light detectors calibration is divided usually to two tasks. One of them is relative calibration of the detectors which is getting of separate calibration coefficient for every detector. Using the sumple of these coefficients one can get the same relative signal for the same light flux from every detector. The task of relative calibration was solved using the the stable light sourse one the same for all the detectors. The Cherenkov light flashes in the atmosphere provide such the universal light sourse. The thing is that the light flux density spectrum has to be the same for every detector with fixed aperture. So comparing the recorded light flux density spectra from all the detectors measured in any relative units the one can get the needed relative calibration coefficients. And even more as the density spectrum don't vary with time then the time variation of recorded spectrum provides measuring and taking into account the relative atmosphere transparency.

The second task is the absolute calibration that means the obtaining of the coefficient between the recalculated relative output signal and the number of photons of the light flash. At this step one needs to know the spectral sensitivity of PMT photo-cathode and the actual wave lenght spectrum of light. The next step is to calculate the number of emitted photons taking into account the actual transparency of the atmosphere and it's wave length dependence.

Two main methods of absolute calibration has been used in Cherenkov light experiments. One of them was usage of light radiator. Block of plexiglass or the layer of pure distilled water played the role of such radiator. Atmospheric muon of cosmic rays crosses the radiator and produces the ammount of Cherenkov light photons which can be easily estimated theoretically. The wave spectrum of radiated photons is similar to that of atmospheric light. The main uncertainties arise from the loss of light during refraction and reflection of light on the borders and from the spectral characteristic of the photo-cathode. These uncertainties cause the total uncertainty of the method of about 25% [6]. The best accuracy for such absolute calibration method of about 18% was claimed by the authors of CASA-BLANCA experiment [7].

The second method of absolute calibration is statistical method [8]. This method has been used in the first experiments in Tunka valley [9] and for the preliminary calibration in the QUEST experiment [10]. It is based upon the measurement of distribution of output amplitudes for small enough but stable input light flashs. The standard deviation of such distribution is determined by Poisson fluctuations of number of photo-electrons. So measuring the first and the second moments of the distribution one can measure the number of photo-electrons, knocked out by the photons of the light flash. But at the step of recalculation from number of photo-electrons to the number of emitted Cherenkov photons the uncertainties in spectral characteristic of PMT for the actual light wave length spectrum and atmospheric transparency cause the total uncertainty of absolute energy calibration of about 25% as for the previous method of calibration.

Such uncertainty being good enough for the first Cherenkov light experiments is insufficient now. Complex experiment QUEST at the EAS-TOP array permitted to join the advantages of both methods: accuracy of absolute calibration of size measurement and good energy resolution of Cherenkov light flux measurement.

3. Experiment QUEST at the EAS-TOP array.

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.) [10]. The wide-angle Cherenkov light detector was based upon QUASAR-370 (37 cm diameter) hemispheric photomultiplier tube. The detectors were installed on five telescopes of the

EAS-TOP array.

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.

The new fitting function, suggested in ref. [10], 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: $P = Q(100)/Q(200)$. Using of the new fitting function improved the accuracy of estimation of mentioned parameters as compared with previous more simple approximations.

4. Simulations for the QUEST experiment

Analysis of CORSIKA simulation has shown the strict correlation between the size/energy ratio and the steepness of the Cherenkov light lateral distribution. This corralation is shown at Fig.1.

The total sumple of 400 events are presened on the fig. 1 for primary protons and iron nuclei of different energies from 1 to 8 PeV for different zenith angles θ from 24° to 39° and for two different models of hadron interaction: QGSJET [12] and SIBYLL [13]. The points, presented at the picture demonstrate the independence of the relation between N_e/E_0 and P both on the mass of primary particle and the hadronic interaction model used for the simulation.

Using the correlation shown on fig.1 one can get the primary energy in experiment from the measurement of N_e and P:

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

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[1].

Similar method of energy reconstruction, but for LDF steepness, estimated at smaller distances from the core $(20 - 100$ m) using more simple exponential fitting function for CLDF, was suggested in ref. [14].

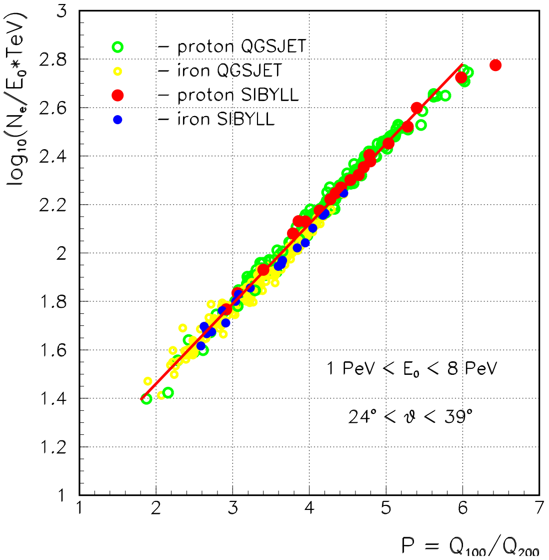

Figure 1. CORSIKA: N_e/E_0 versus the CLDF steepness P

During the QUEST experiment the energy could be measured at every event by two methods one of them $SIZE/CLDF$ discribed above and more simple method of recalculation from Cherenkov light flux at a fixed core distance Q_{175} to the primary energy. Correlation of Q_{175} and primary energy E_0 for the same simulated sumple of events is shown at fig. 2.

Primary energy E_{CHER} is almost proportional to the parameter Q_{175}: $E_{CHER} = C_Q \cdot Q_{175}^{0.94}$.

The main problems of this "classical" method are the bigger sensitivity of the coefficient C_Q to the primary mass composition and the uncertainty of the absolute calibration of Cherenkov light flux Q_{175}. The last uncertainty may be treated as an additional uncertainty of the same coefficient C_Q.

But if one takes into account the experimental errors he finds that the energy resolution of

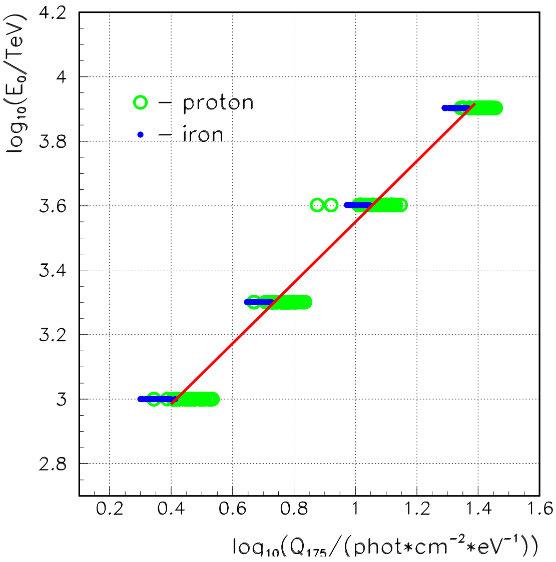

Figure 2. CORSIKA: E_0 vs Q_{175}

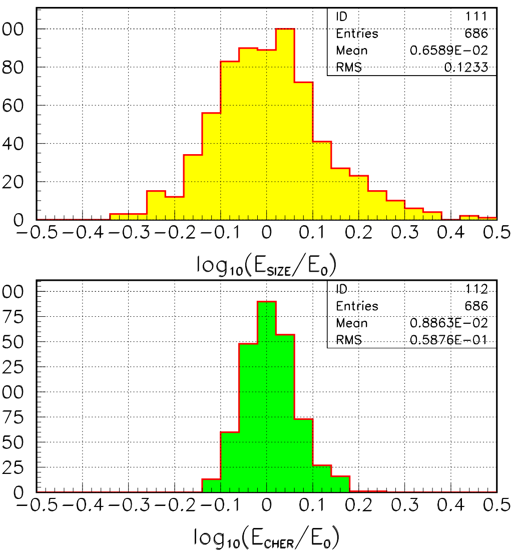

Figure 3. Model of experiment: energy resolution

the second method is at least two times better than for the first one. Fig.3 shows the result of simulation of energy resolution for both methods with the special code "model of experiment" based upon the CORSIKA simulation results and taking into account all the experimental errors as well as the primary energy spectrum, distribution of primary arrival directions and the real array geometry. The mass composition of equal ammount of primary protons and iron nuclei was supposed in the "model of experiment" simulation.

One can see from fig.3 that energy resolution is about 30% for the first $SIZE/CLDF$ method and about 15% for the second $CHER$ method. The main reason of bigger relative error in energy reconstruction by the first method is the error in reconstruction of experimental CLDF steepness P.

So to join the advantages of both methods the mean experimental ratio $< E_{SIZE/CLDF}/Q_{175}^{0.94} >$ has been used as the coefficient for the absolute calibration of Cherenkov array response. So the final expression used for energy measurement was:

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

5. QUEST experimental results

The data aquisition was carried out during the clear moonless night in 1998 - 2000. The experimental data obtained during the 140 hours of array operation has been used for the analysis. The total statistics of 594 events with $E_{CHER} \geq 3 \cdot 10^{15}$ eV inside the effective area and solid angle of the array was obtained.

The figure 4 shows the distribution of ratio of primary energy estimated by two methods.

Figure 5 presents the integral primary energy spectrum obtained in QUEST experiment.

The filled point represents the integral intensity for energy more or equal to $3 \cdot 10^{15}$ eV:

$$I = (2.3 \pm 0.1^{stat} \pm 0.4^{syst}) \cdot 10^{-7},$$

$$[\mathrm{m}^{-2} \cdot \mathrm{s}^{-1} \cdot \mathrm{ster}^{-1}].$$

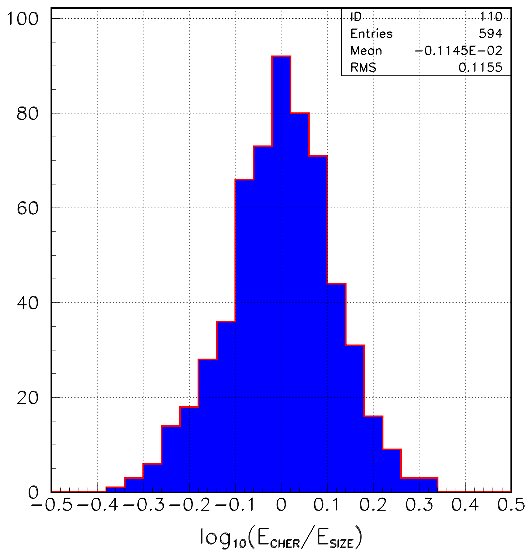

Figure 4. Comparison of E_{CHER} and $E_{SIZE/CLDF}$ at every event

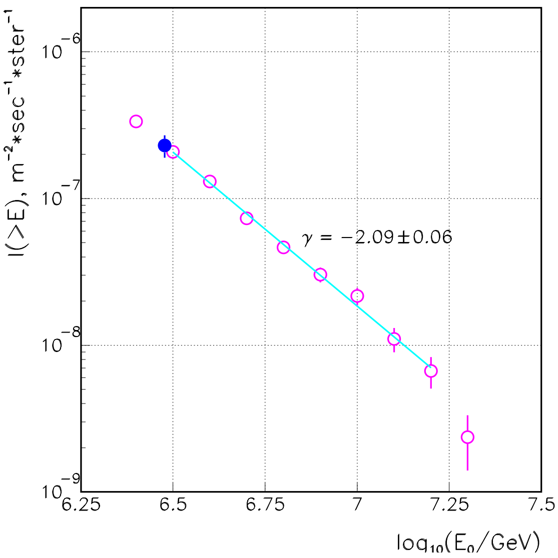

Figure 5. Integral Energy Spectrum

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% [1].

The maximal systematic shift of calibration coefficient, connected mostly with the lack of knowlege of the real mass composition, was estimated by simulation with "model of experiment" code assuming different mass composition. The maximal error in coefficient C_Q in expression 2 of about 8% was obtained for pure proton composition. The maximal possible systematic uncertainty of the thrshold energy estimated as a root mean square of the sum of squares of these two values is about 10%.

6. Usage of QUEST results at Tunka-25 experiment

The results of QUEST experiment were used for the analysis of the data of Tunka experiment [5]. The new fitting function mentioned above has been used for the reconstruction of the main EAS parameters: core position - x, y; light flux at a core distance 175 m - Q_{175} and the LDF steepness - $P = Q(100)/Q(200)$. Figure 6 presents some examples of reconstructed LDF for the experimental events of different primary energy. The threshold of data acquisition with 100% efficiency was about $8 \cdot 10^{14}$ eV.

The primary energy E_0 has been obtained from Q_{175} [photon $\cdot$ cm$^{-2} \cdot$ eV^{-1}] with the relation:

$$E_0 = C_T \cdot Q_{175}^{0.95}.$$

The absolute energy calibration, based upon the results obtained with the QUEST experiment, was made by two steps. First, the energy of every event was estimated with the preliminary calibration coefficient, obtained with the statistical method of PMT response calibration as it was discribed above. Then the total integral energy spectrum is constructed. It is compared with the reference integral intensity of primary cosmis rays, obtained in QUEST experiment as discribed

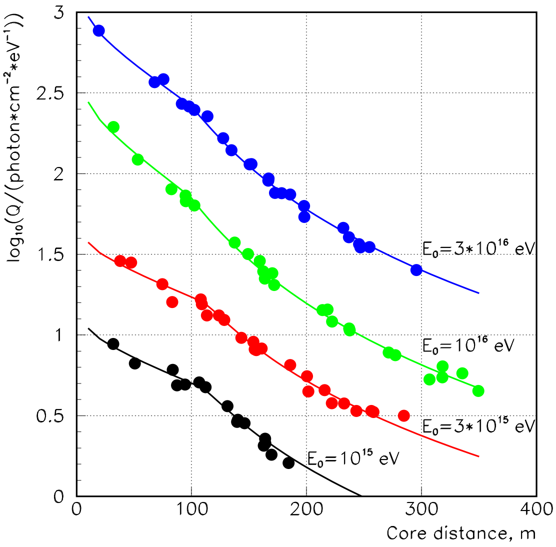

Figure 6. Using of Cerenkov light LDF for reconstruction of EAS parameters in Tunka experiment

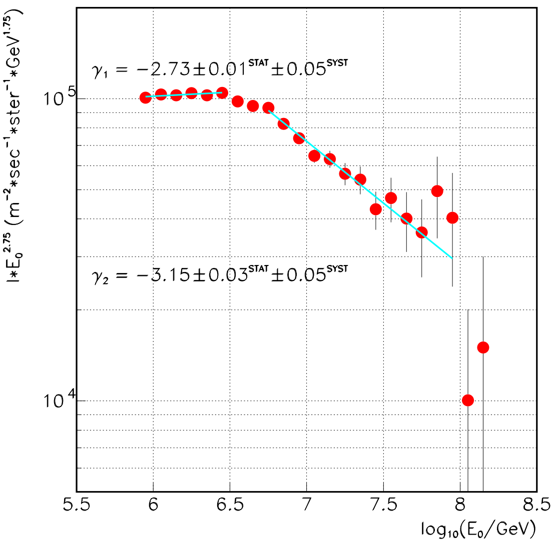

Figure 7. Differential energy spectrum: power law fitting

above. The energy log difference between the point of two spectra for the reference intencity is treated as a correction of the preliminary estimated energy log. Every individual energy is corrected to this value, and the corrected energies are used for the differential energy specrtum reconstruction. This method provides the uncertainty of absolute energy less than 10

Differential energy spectrum obtained in Tunka-25 experiment is shown at fig. 7.

140000 events with $E_0 \geq 8 \cdot 10^{14} eV$, and $\theta \leq 25°$ obtained during about 300 hours of operation are included into the sprctrum. About 10000 events has energy $E_0 \geq 3 \cdot 10^{15} eV$. The one using the power law fitting of the spectrum may conclude that the change of power law index occupy the energy range from $\sim 3 \cdot 10^{15}$ to $\sim 6 \cdot 10^{15}$ eV.

It seems to be intersting to compare the result of Tunka experiment obtained with the extreamly high energy resolution (15%) and the absolute energy uncertainty less than 10% with the results of some other recent experiments in the wide energy range. Such comparison is presented at fig. 8.

At the lowest energy we show the most recent data of the new analysis of direct ATIC-2 balloon experiment [15].

At the "knee" region at least 5 more experiments give the primary energy spectra very similar to the Tunka-25 one. They are HEGRA-AIROBICC [16], Tibet [3], EAS-TOP [1], KASCADE [17] and Moscow State University [18].

Situation becomes much worse at very high energies. One can see the difference between the results of Yakutsk [19] and AGASA [20] and between AGASA and HighRes [21]. The main reason of big difference in the results seems to be the big uncertainty in absolute calibtarion in this energy region. EAS Chernkov light measurements can help to reduce the uncertainty if to spread the region of EAS Cherenkov light measurements to higher energies. To solve the problem of absolute energy calibration and get the energy spectrum with high resolution till the energy 10^{18} eV the Tunka Collaboration plans to install the new

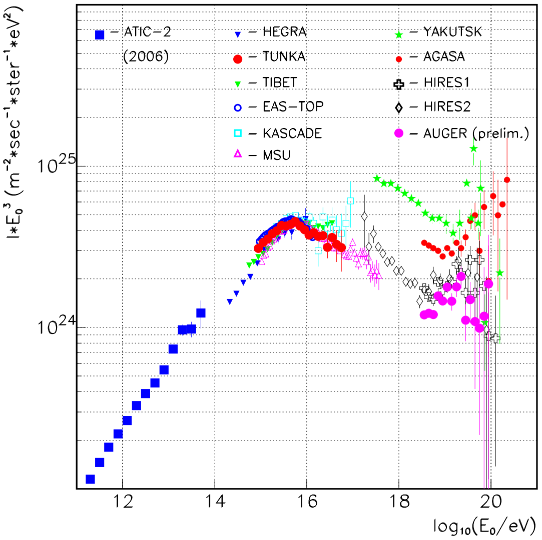

Figure 8. Comparison of some recent energy spectrum measurements in wide energy range

array of 10 times higher area Tunka-133 in the Tunka valley [23].

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