The advantages of high mountain observation levels for astroparticle studies

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The basic problems in astroparticle physics, namely mass composition estimation and energy spectrum around the "knee" region are described. Several challenges connected with experiment constraints are discussed. Problems such as constant efficiency selection of air showers and multicharacteristics measurements are pointed out.

Recent simulation with CORSIKA code with corresponding hadron interaction models FLUKA and QGSJET are presented, namely lateral distribution of atmospheric Cherenkov light flux at high mountain observation level. The application of obtained results for mass composition, energy estimation of primary cosmic ray around the "knee" is shown. The gamma hadron separation is demonstrated. The application for ground based gamma astronomy is discussed.

Introduction

After the discovery of cosmic rays by V. Hess there are still two main problems: the origin and acceleration mechanisms of primary cosmic ray flux. It is regarded that, the bulk of cosmic rays originate from the Galaxy, the part below the "knee" (a sudden steepening of the cosmic-ray energy spectrum around 4×10^{15} eV) comes from Galactic supernovas, particles being accelerated by the shocks in the supernovas remnants (SNR).

Usually the explanation of the "knee" of the spectrum is based on the SNR diffuse shock acceleration mechanism [1] limits. In this model the galactic supernovas are the only galactic candidate with sufficient energy. The supernova diffuse shock acceleration mechanism can produce high energy particles up to some maximal energy, which is limited by the lifetime of the shock wave.

Other possibility is presented in the case, when the particles are so energetic and they can no longer be confined in the acceleration region.

Obviously the energy range 10^{14} - 10^{16} eV is recognized as crucial to the understanding cosmic ray acceleration, because it appears to mark a transition from one process of acceleration to another.

Another possible explanation of the "knee" may be a fundamental change in the physics of nuclear interactions at these very high energies

In order to answer these problems it is necessary to measure relative contribution of the different group of nuclei and their energy. The elemental composition of the high energy cosmic rays is a powerful constraint on theories of their origin and propagation. To distinguish among models of cosmic ray origin the nuclear composition should be determined at all energies, especially around the "knee".

Therefore the measurements of the individual cosmic ray spectrum and the precise estimation of mass composition are very important in attempt to obtain more detailed information about the sources of primary cosmic ray and to build an adequate model of cosmic ray origin and acceleration mechanisms.

At experimental point of view it is very important to provide data with high statistics and as less as possible uncertainties.

Thus the discussed above problems are both theoretical and experimental.

Cosmic ray measurements

The energy spectrum and chemical composition of primary cosmic rays have been determined from direct observation above the Earth's atmosphere using balloons and spacecraft [2]. This technique is limited by the small size of the detectors and the short exposure times. As a result no direct observations are available above 10^{14} eV.

Above 10^{14} eV the only possibility for cosmic ray detection and measurement is ground based i.e. the detection of one or several of the components of secondary cosmic ray.

Therefore in the interesting region of the "knee" in the spectrum and above, information on composition has to be inferred from indirect measurements of air showers at sea level or mountain altitudes, by using large area detectors for long periods of time.

The secondary CRs are usually measured with help of air shower arrays.

At the same time one of the most convenient techniques in cosmic ray investigation is the atmospheric Cherenkov technique i.e. the detection of the Cherenkov light in extensive air shower (EAS). The Cherenkov light generated in EAS was observed first by Galbraith and Jelly in 1953 [3].

As example the Whiplle telescope which is based on imaging the air shower detected CR signal from Crab Nebula. This technique was proposed by Weeks and it is based of an array of photomultipliers at the focal plane of the telescope. The Cherenkov camera with good pixilation permits to discriminate the hadronic and electromagnetic showers and moreover to follow the development of the cascade into the atmosphere.

The detection of the air Cherenkov light at ground level using an array of telescopes or photomultipliers contrary to the image technique is also a powerful tool for the both of the mentioned above problems - gamma astronomy [4, 5] and the all particle energy spectrum [6].

Obviously the connection between the nature of the primary particle and air shower observations requires the detailed understanding of particle interactions at very high energies and forward scattering angles where no information is available from accelerator-based experiments.

In this connection the reconstruction methods are very model dependent i.e. the information of primary particle nature depend on several assumptions and constraints connected with hadron interaction models.

High mountain cosmic ray stations

Presently several experiments reported significant results about primary CR spectrum and mass composition [2, 7] Fig.1.

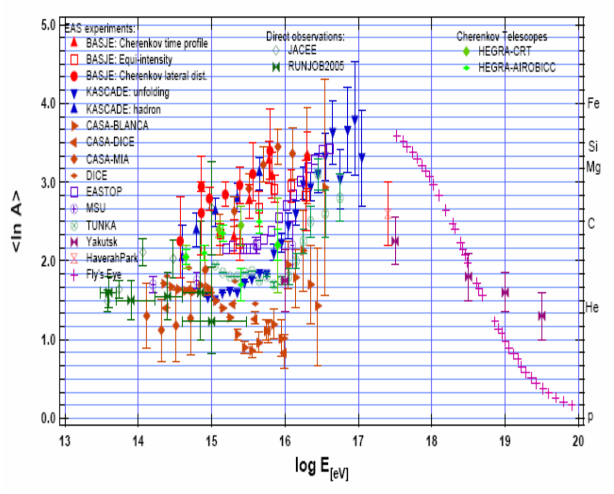

Fig.1. Mean logarithmic mass of primary CR

At the same time the study of extensive air showers of higher energies at an early stage of development where showers present a minimum of fluctuations is very important.

The very high mountain observation levels as example Chacaltaya (540 g/cm$_2$) 5200 m a.s.l. corresponds to the maximum development of the showers in the energy range of 10 - 500 TeV, giving a maximum detection probability. Moreover the fluctuations in the development of the showers are much lower at high mountain observation level than at lower altitudes.

The high mountain observation levels permit to estimate with big precision the atmospheric depth at which the maximum shower development occurs, which is the most important feature of shower longitudinal development. This is connected also with determination of the muon/electron ratio as well arriving time distribution of EAS components, which is another powerful indicator of the primary particle nuclear identification.

All the mentioned above features are strongly related to reconstruction methods.

Presently several experiments are carried out at high mountain observation level**:** the Chacaltaya Cosmic Ray Laboratory (the Andes, Bolivia, 5200 m a.s.l., 540 g/cm^2); the Ak-Arkhar Cosmic Ray Experimental Site (the Pamir, Tajikistan, 4400 m a.s.l., 600 g/cm^2); the Yangbajing High Altitude Cosmic Ray Laboratory(Tibet, China, 4300 m a.s.l., 606 g/cm^2); the Tien Shan High Altitude Mountain Research Station (Tien Shan, Kazakhstan, 3300 m a.s.l., 700 g/cm^2); the Aragats Cosmic Ray Observatory (Mt.Aragats, Armenia, 3200 m a.s.l., 710 g/cm^2); the GRAPES experimental site (Ooty, India, 2200 m a.s.l., 800 g/cm^2); the High-Altitude Water Cherenkov (HAWC) experimental site (Parque Nacional Pico de Orizaba, Mt. Sierra Negra, Mexico, 4100 m a.s.l., 620 g/cm^2); BEO Moussala Bulgaria (Rila mountain Bulgaria, 2925 m a.s.l., 700 g/cm^2).

High mountain cosmic ray studies

The BASJE (Bolivian Air Shower Joint Experiment) group, measurements of cosmic ray composition around the knee by using three independent observation techniques are carried out: those are measurements of arrival time distribution of Cherenkov light associated with air showers [8], lateral distribution of Cherenkov lights [9], and the longitudinal development curves obtained from equi-intensity cuts using shower size spectra for various arrival directions [10].

Recently the air shower array were improved Fig. 2.

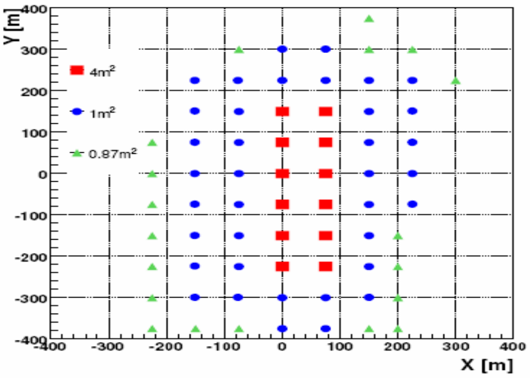

Fig.2. BASJE Lateral distribution of Cherenkov light flux in EAS produced by primary protons in the energy range 10^{11} *–*10^{13} *eV at 536g/cm*^{2} *observation level*

This array represents 68 scintillation detectors arranged in an area of 60x60m. The new air shower array in this project is constructed by extending the detector separations to 75m over a wider filed of 700x500m. Each detector is comprised of plastic scintillator plates and a photo multiplier tube (PMT), and measures local densities and arrival times of shower particles. In the inner region of the array, twelve detectors of 12 m^2 are installed, whereas the other detectors have smaller scintillators of 1 m^2 or 0,87 m^2 .The inner twelve detectors are used as the triggering detectors.

Obviously a reconstruction procedure is necessary. In this connection a detailed Monte Carlo simulation of atmospheric Cherenkov light in EAS is carried out.

Lateral distribution of atmospheric Cherenkov light

Initially for the aims of HECRE experiment proposal [11] a CORSIKA code [12] version 6.5 has been used for simulation of the development of EAS. The FLUKA 2006 [13] and QGSJET II [14] hadronic interaction models have been assumed respectively for low and high energy hadronic interactions.

The observation level was of 5200 m a.s.l. (540 g/cm^2) which is near to the shower maximum.

The simulated particles are primary Proton, Iron, Helium, Oxygen nuclei. The lateral distribution of atmospheric Cherenkov light flux is obtained integrating over time and angle the incoming Cherenkov photons.

The results for primary nuclei are presented in Fig. 3 and Fig. 4 for 10^{13}-10^{15} eV and 10^{15}-10^{17} eV respectively. In Y axis is shown the Cherenkov light density Q(R) measured in photons per m^2 and the corresponding standard deviation of the obtained Cherenkov light flux (the error bars). In X axis is shown the core distance in meters.

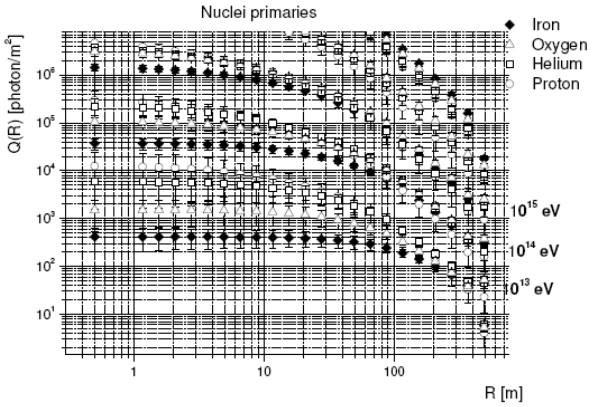

Fig.3. Lateral distributions of Cherenkov light flux in EAS produced by primary hadrons in the energy range 10^{13}–

During the simulations the impact of atmospheric conditions [15] on generation and propagation of Cherenkov radiation is taken into account.

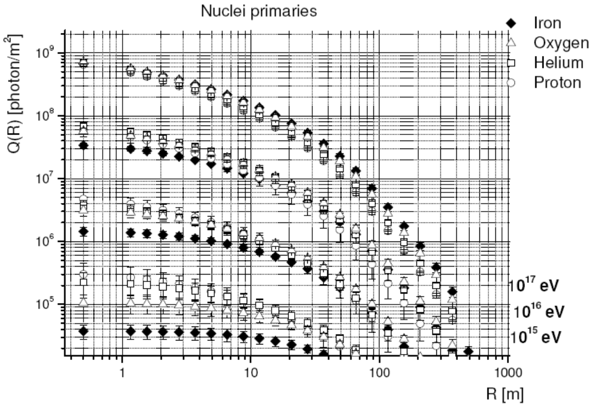

Fig4. Lateral distributions of Cherenkov light flux in EAS produced by primary hadrons in the energy range 10^{15}–10^{17} eV at 536g/cm² observation level

The majority of the Cherenkov photons are produced near to the shower maximum [16] in the energy range around the "knee".

The observed difference is significant near to the shower axis and in the low energy region i.e. around energies of some 10^{14} eV. At the end of the distribution the difference is smaller.

However the significant differences observed in the fluctuations are well seen, especially the gradient of the distribution.

Obviously in the energy range below the "knee" the obtained lateral distributions of Cherenkov light flux in EAS initiated by primary nuclei is between the Cherenkov light flux generated by proton and iron nuclei as incoming showers.

Generally the shape of the distributions is very similar with differences of the density values and the slope. At the same time the relative fluctuations varies as a function of the energy of the initial primary and as well the type.

The obtained differences are the basis of new method for energy estimation and mass composition determination of primary CR based only on Cherenkov light registration [17, 18].

The method is based on the parameterizations of lateral distribution of Cherenkov light flux densities and solution of inverse problem. The proposed non-linear fit (1) is the same for each distribution.

$$Q(R)=\frac{\sigma e^{a} e^{-\left[\frac{R}{\gamma}+\frac{R-r_0}{\gamma}+\left(\frac{R}{\gamma}\right)^2+\left(\frac{R-r_0}{\gamma}\right)^2\right]}}{\gamma\left[\left(\frac{R}{\gamma}\right)^2+\left(\frac{R-r_0}{\gamma}\right)^2+\frac{R\sigma^2}{\gamma}\right]} \quad (1)$$

The distinction between the different primaries is carried out on the basis of the different model parameters and χ^2 of the reconstructed distribution. The energy estimation is made by integration of the reconstructed lateral distribution (2).

$$N_q = 2\pi\cos\theta\int Q(R)RdR \quad (2)$$

where Nq is the total quantity of Cherenkov photons in the shower.

Thus the energy is

$$E=\kappa f(N_q)$$

The detailed study of the model parameters as a function of the energy and type of the initiated primary, permits to build a bank of model parameters, corresponding to different primaries.

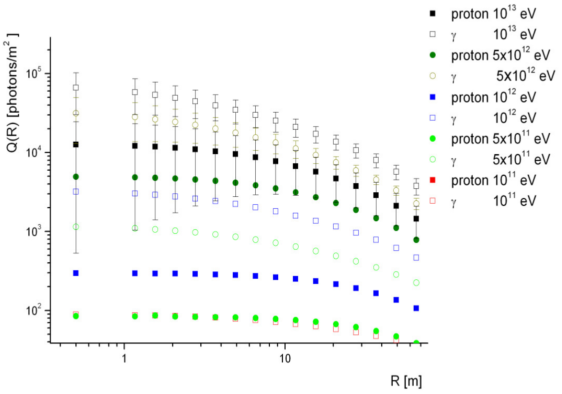

Fig.5.Difference between proton and gamma quanta produced Cherenkov light in EAS

Similar simulations are carried out for gamma quanta incident particles with practically the same data sets in CORSIKA code. The aim is to propose method for gamma-hadron rejection [19], which is necessary for the needs of ground based gamma astronomy.

The main difference comparing to the lower observation levels is that one can not observe a typical for lower observation levels hump i.e. the characteristic ring of Cherenkov photons which appears between 90 and 120 m from the shower axis in the case of gamma quanta induced showers. This is due essentially to the high mountain observation level and thus the not so important influence of the atmosphere layer to the refractive index.

The difference between lateral distributions of Cherenkov light flux in EAS initiated by proton and gamma showers in the energy range 10^{11}-10^{13} eV is presented in Fig. 5.

Constant efficiency selection

The calibration of the direct and indirect methods for primary cosmic radiation studies and the constant efficiency selection of EAS at given observation level are one of the most important problems in the field of experimental cosmic ray studies.

In this connection a new experiment at Chacaltaya observation level was proposed [20]. It is connected with new shower selection devoted to unbiased estimations of the mass composition and energy spectrum of the primary cosmic radiation at energies 10^4 – 10^5 GeV in an attempt to carry calibration between the direct and indirect methods for primary cosmic flux studies [21].

The obtained Cherenkov light lateral distributions are used for the proposition of new selection parameter based only on Cherenkov light measurements [22], which permits to select hadron with constant efficiency not dependent on the atomic number of the initiating primary particle.

The selection parameter is defined as

$$\eta(R) = \frac{\lg[Q(R_1) - Q(R_2)]}{\lg Q(R_1)} \qquad (3)$$

where R_1=65, R_2=208 from the shower axis, Q(R) are the corresponding Cherenkov light flux densities.

Summary and Discussion

The worldwide distribution of High Mountain Observatories provides a unique opportunity for performing contemporary measurements under different geomagnetic/altitude conditions and for collecting long-term data series. In this connection in this paper are presented several results based on Monte Carlo simulation with CORSIKA code, namely lateral distribution of Cherenkov light flux in EAS, which give new possibility for cosmic ray studies.

The described results are connected with fundamental problems of primary CR studies at theoretical and experimental point of view and application of modern numeric methods [23].

The advantages of high mountain observation levels are mainly related to shower development and permit at experimental point of view to obtain flatter distribution comparing to lower observation levels. Moreover, the attenuation of Cherenkov light flux at smaller, thus it is possible to register both gamma quanta and CR ate lower energies.

In this connection the high mountain observation levels give the opportunity to intercalibrate direct and indirect methods for obtaining the energy spectrum and mass composition of the primary cosmic flux at energies around the "knee".

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