

Measurements of EAS muon energy – the key to solution of primary cosmic ray energy spectrum problem

A.A. Petrukhin

Moscow Engineering Physics Institute (State University), 115409 Moscow, Russia

Abstract. The present situation with EAS investigations is analysed. The key role of EAS muon energy measurements is underlined. Experimental possibilities of the solution of this task are considered.

Keywords: primary cosmic rays, EAS, muons

I. INTRODUCTION

Energy spectrum and composition are the main characteristics of primary cosmic rays. Results of their investigations are widely used for the choice of cosmic ray origin model. Unfortunately, information about cosmic ray energy spectrum and composition above 10^{15} eV can be obtained only from results of EAS investigations. In this case, to two unknown characteristics of cosmic rays mentioned above a new unknown function is added: interaction model. Of course, results of studies of interaction model at lower energies which were obtained in accelerator experiments are used. But, on the one hand, the region of small scattering angles, which is very important for cosmic ray interactions, in collider experiments has been studied very poor. On the other hand, the use of the model which is in a good agreement with experimental data at lower energies suggests that no new physical phenomena can appear at higher energies. On the face of it, the task to find parameters of three unknown functions is not so difficult since in EAS investigations many different characteristics are studied. In present paper the review of this approach is done and some new ideas are considered.

II. PRESENT STATUS OF EAS INVESTIGATIONS

In Fig. 1, basic measured characteristics of EAS are given. Here N_{ei} is the number of charged particles (mainly electrons) in i -th detector of shower array; ΔE_h is the energy deposit of EAS core in central calorimeter; C. C. – cascade curve of EAS development in the atmosphere measured by Cherenkov or fluorescent detectors; x_{max} – the depth of cascade curve maximum; $N_{\mu j}$ – number of muons measured in j -th muon detector. EAS energy and type of primary particle are evaluated taking into account these observables and their lateral distributions.

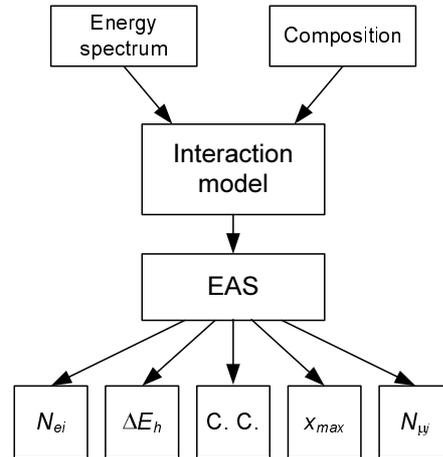


Fig. 1: Scheme of cosmic ray energy spectrum and composition study in EAS investigations.

A. EAS energy

Two approaches to EAS energy evaluation are usually used. In the first one

$$\begin{aligned}
 E_{EAS} &= k_e \left(N_e = \sum_{i=1}^{n_e} N_{ei} \right) = \\
 &= k_\mu \left(N_\mu = \sum_{j=1}^{n_\mu} N_{\mu j} \right) \quad (1)
 \end{aligned}$$

Coefficients k_e and k_μ are determined from models of EAS development, Monte-Carlo simulations and other calculations. This approach is the simplest one. In the second approach, N_{ei} and $N_{\mu j}$ data are used to obtain the location of EAS axis and after that lateral distributions of electron or/and muon components around the axis $\rho(N_{ei}, N_{\mu j}, r, \theta)$ are obtained which are compared with theoretical model (f. e. Greisen-Nishimura function). This approach is more accurate, but depends on theoretical model. The main drawback of EAS energy evaluation by the number of charged particles is unknown level of EAS development, which is usually evaluated by means of parameter s – EAS age. Since electrons are absorbed in the atmosphere, for inclined EAS only muon data $N_{\mu j}$ can be used. However it is necessary to underline that in all these cases EAS energy can be evaluated, but not primary particle energy. The application of Cherenkov and fluorescent detectors for measurements of the full cascade curve of EAS development in the atmosphere allows obtaining more

accurate and less model independent evaluation of EAS energy.

B. Type of primary particle

Usual particles generating EAS are protons or nuclei. Contribution of γ -quanta and electrons is very small. Two parameters – x_{\max} and N_{μ}/N_e – are usually used to evaluate mass number A of particle which generates shower in the atmosphere. The dependence of these parameters on A is the following: at increasing A , the value x_{\max} is decreased and N_{μ}/N_e is increased. Theoretical predictions give relatively distinct separation between showers from protons and f. e. iron nuclei (Fig. 2).

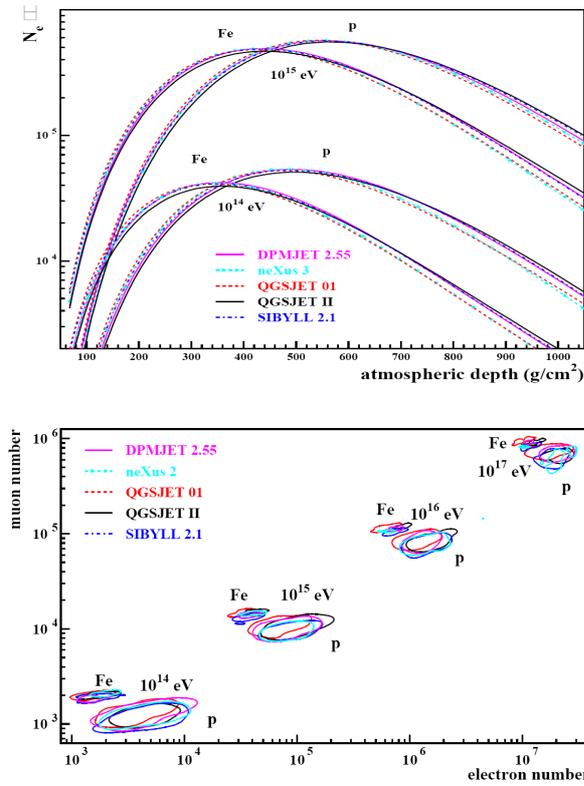


Fig. 2: Dependences of cascade curve shape (top) and N_{μ}/N_e (bottom) on energy for primary protons and iron nuclei [1].

Experimental measurements give nearly continuous distributions from protons to iron nuclei (Fig. 3 [2]). Therefore in principle it is possible to evaluate average value A (or $\ln A$) only, though by using a more sophisticated technique of experimental data treatment one can try to separate contribution of different groups of nuclei. Of course these attempts will be model dependent.

C. Experimental data

In spite of intensive EAS investigations over a long period and numerous constructed arrays, clear and non-contradictory knowledge about energy spectrum and composition of primary cosmic rays has not been obtained yet. The present situation is illustrated in Fig. 4

with well-known results of EAS investigations. The first conclusion which can be done – a large straggling between various data concerning the composition. It is necessary to note that in Fig. 4 some average data are presented. Original data have even more large straggling, in spite of the fact that “experimental” data after introducing different cuts are published (see Fig. 3).

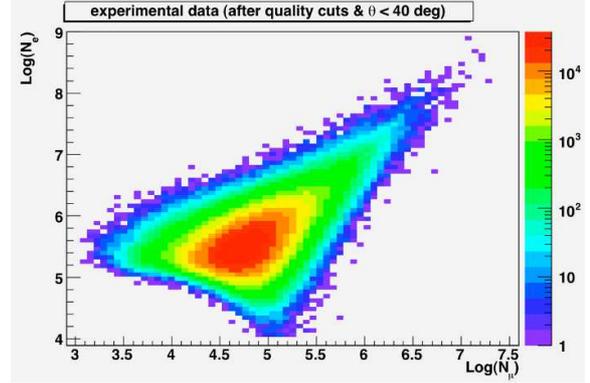


Fig. 3: Results of value N_{μ}/N_e investigations.

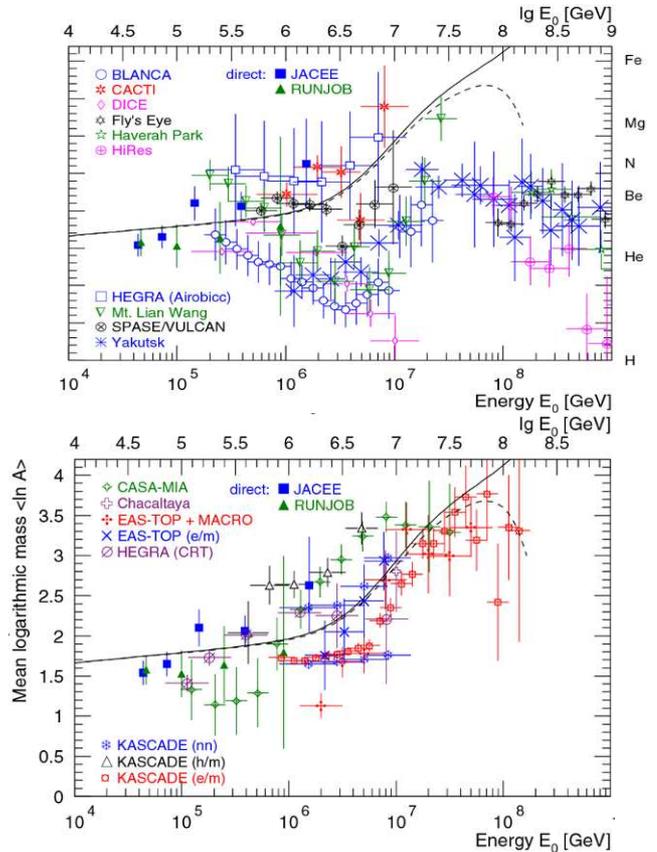


Fig. 4: Results of cosmic ray composition investigations by means of x_{\max} (top) and N_{μ}/N_e (bottom).

III. DISCUSSION

The main conclusion which can be done from the above consideration is the following. The real straggling between the measured parameters of EAS is several times (if not orders) more than predicted values. Two basic reasons of this situation are possible. The first one is not adequate technique of detectors of EAS investigations. Really 1) the total area of EAS array (in the best case) is about 1% at EAS area; 2) applied detectors measure total ionization effect but not the number of particles (this point is especially important for muon number measurements, taking into account that their energy loss increases with increasing energy); 3) the used methods of treatment of experimental data (χ^2 , maximum likelihood, etc.) decrease the measured straggling.

The second reason is the use of non-adequate theoretical models for description of particle interaction and EAS development above accelerator energies. It is known that the first drastic change of energy spectrum and composition (the knee) appears at 3-5 PeV. But approximately at the same energies numerous unusual events in various cosmic ray experiments begin to appear, too (see [3]). If to assume that both these phenomena (unusual events and the knee appearance) are connected with each other, new theoretical approaches have to be developed (new heavy particles, resonance states, quark-gluon plasma, etc.). But in any case for explanation of the knee by changing the interaction model (without changing primary cosmic ray spectrum) it is necessary to explain missing energy – the difference between primary particle energy and measured EAS energy. If not to introduce new undetectable particles, the only particles which can take away the “missing” energy are muons and neutrinos. At that their energy spectrum will be very hard (Fig. 5), and small total number of these particles can take away considerable energy. These particles can be named VHE muons and neutrinos, and the only possibility to find VHE muons are their energy measurements. Unfortunately in most part of existing EAS arrays appropriate muon detectors are absent.

Alternative approach is the construction of EAS array around existing muon detectors, which can be used for VHE muon searches. As an example, BUST – “Andyrchi” can be taken [5]. But apparently the best possibilities for this purpose at present gives Russian-Italian complex NEVOD-DECOR [6], which allows detect muon bundles in the wide zenith angle interval (up to 85°) by coordinate detector DECOR and measure their energy deposit in Cherenkov water detector NEVOD. As a result the dependence of energy deposit on muon multiplicity will be obtained. VHE muons have to give large fluctuations, increasing with energy in this distribution. Of course, more convincing data can be obtained if a standard EAS array will be constructed around experimental complex NEVOD-DECOR. In this case it will be possible not only to observe VHE muons

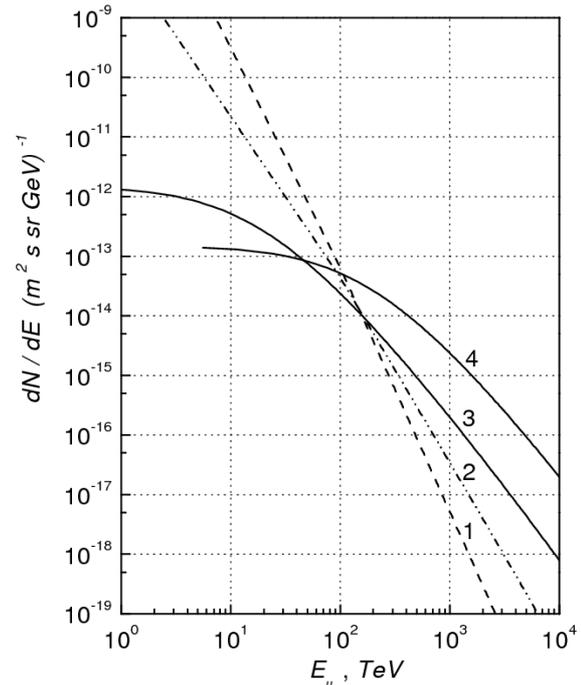


Fig. 5: Differential muon energy spectrum. 1 - muons from π^- and K^- decays; 2 - upper limit of prompt muons from charm production; 3, 4 - estimated minimum and maximum contribution of new processes [4].

but to search processes of their generation.

It is necessary to note that VHE muons can distort results of muon number measurements since their energy loss is several times more than for usual EAS muons. Additional ionization effects in muon counters will be interpreted as increasing number of muons, which corresponds to more heavy primary particle generating this EAS.

IV. CONCLUSION

Measurements of muon energy in EAS is really a difficult task, but without its solution there is a little chance to find adequate description of primary cosmic ray energy spectrum and composition and their possible changes.

V. ACKNOWLEDGMENTS

This work was supported by Federal Agency for Education (grants RNP.2.1.1.8641 and RNP.2.1.1/664).

REFERENCES

- [1] D.Heck, CORSIKA School, November, 2008 (<http://www-ik.fzk.de/~corsika/corsika-school2008/>).
- [2] G.Navarra, Symposium “Advances in Cosmic Ray Studies”, Karlsruhe, 30-31 March, 2009 (<http://www-ik.fzk.de/kascade-symposium/>).
- [3] S.Slavatinski, Nucl. Phys. B (proc. Suppl.), v.122, p.3, 2003.
- [4] A.Petrukhin, 27th ICRC, Hamburg, v.5, p.1768, 2001.
- [5] V.Petkov, A.Bogdanov et al., 29 ICRC, Tsukuba, v.1, p.57, 2003.
- [6] A.Petrukhin, NEVOD-DECOR experiment, Symposium “Advances in Cosmic Ray Studies”, Karlsruhe, 30-31 March, 2009 (<http://www-ik.fzk.de/kascade-symposium/>).