Carpet-3 - a new experiment to study primary composition around the knee

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We propose a new experiment to study primary composition around the knee. The Carpet-3 EAS array is the further development of the Carpet-2 EAS array (1700 m a.s.l., Baksan Valley) and it is supposed to be a multi-component and multi-purpose array detecting, in the EASes with $E > 10^{13}$ eV, electrons, gammas, muons (with a threshold energy of 1 GeV), hadrons (with energies more than 30 GeV), and thermal neutrons as well. The experimental data are to be used in the multi-component analysis to make conclusions about the composition of the primary cosmic rays.

1. Introduction

The nature of the knee in the primary cosmic ray spectrum at $E_k \approx 3 \times 10^{15}$ eV, where the power law index $\gamma$ is changed from $\gamma \approx 2.7$ to $\gamma \approx 3.1$, is one of main problems in modern high energy astrophysics. Different models for acceleration and propagation of high-energy cosmic rays in the Galaxy predict different shapes of the knee. Especially intriguing is the fact that the knee energy is very close to the maximum attainable energy for protons accelerated in the shock front of SNRs [1]. Today’s view is that the origin of the knee could provide an answer to the puzzling problem of cosmic ray origin.

The knee in the shower size spectrum at about $10^6$ particles was first observed by the MSU group in 1958 [2] and at the same time the astrophysical interpretation of the knee, namely, the steepening of the primary cosmic ray spectrum, was proposed. Since then many experiments have been carried out, and breaks in the size spectra of Extensive Air Shower (EAS) have been found for its different components: electromagnetic (e.m.), muonic, Cherenkov light, and hadronic. It is obvious inconsistency between characteristics of these breaks that does not allow us to give a final conclusion concerning the shape of the knee in the primary spectrum [3]. What is more, the dependence of the mean atomic number of primary cosmic rays on primary energy around the knee obtained in different experiments have an enormous scattering - from pure protons to pure irons. These contradictions gave rise to different alternative explanations of the knee: e.g., the knee could be a consequence of some change in the hadronic interaction properties [4] or just a methodical effect [5].

Last decade the study of the knee was carried out with modern EAS arrays able to simultaneously register different EAS components and the EAS inverse approach for reconstruction of primary energy spectra has been developed (see [6] and references therein). It should be noted that this approach is based on different model-dependent EAS simulations with the effect that the reconstructed primary energy spectra differ distinctly. It is quite disappointing to see that the primary energy spectra reconstructed at different EAS arrays differ even when obtained with the same interaction model. Usually modern EAS arrays measure characteristics for two EAS components: the muon (GRAPES-3, GAMMA) or hadronic (Tibet) components are registered in addition to the electromagnetic one. With the exception of the KASCADE EAS array which can register both muon and hadron components in addition to the electromagnetic one, however for reconstruction of primary mass group energy spectra only data from electromagnetic and muon component were used [7]. Thus, it is obvious that solution of the knee problem demands an array measuring all possible EAS parameters with high precision.
2. Carpet-3 EAS array

The Carpet-3 EAS array (Fig.1) is the further development of the Carpet-2 EAS array [9]. The central part of the array (the Carpet proper) consists of 400 individual liquid scintillation detectors of 0.5 $m^2$ each. Six outside points have 18 scintillation detectors each. The signals from the latter are used for timing and for EAS's arrival direction reconstruction.

Muon detector (MD) is situated in the underground tunnels under 2.5 m of soil absorber (500 $g/cm^2$). The distance between MD and Carpet centers is 48 m. At present MD consists of 175 plastic scintillation detectors placed in the central tunnel. Each detector has an area of 1 $m^2$. The detectors are attached to the ceiling of the underground tunnel. MD’s area is supposed to be enlarged from 175$m^2$ to 630$m^2$, the effect of such enlargement is presented in Fig.2.

The important part of the array will be the thermal neutron detectors (TND) [11]. We use a thin layer of a mixture of old inorganic scintillator ZnS(Ag) with LiF enriched in $^6\text{Li}$ up to 90%. Thermal neutrons are recorded due to $^6\text{Li}(n,\alpha)^3\text{H}+4.78$ MeV reaction. ZnS scintillator is the best scintillator for heavy particle detection and it produces $\sim$ 160000 light photons per one captured neutron.

![Fig.1. Carpet-3 EAS array. 1-6 - outside points, 7 - Carpet, 8 - planned Muon Detector (MD) (10 - present MD), 11-13 - outside points with thermal neutron detectors (TND).](image)

![Fig.2. Distribution of the number of muons in MD for the present ($S = 175m^2$) (labelled ‘1’) and planned ($S = 630m^2$) (labelled ‘2’) MD’s area for primary iron nuclei of $E_0 = 10^{15}$ eV with EAS axes in Carpet center (CORSIKA, QGSJet01 + GHEISHA, [8]). For the present MD’s area: $N_{\mu}^{MD} = 21.3$, $\sigma(N_{\mu}^{MD}) = 4.8$, $\frac{\sigma(N_{\mu}^{MD})}{N_{\mu}^{MD}} = 0.23$. For the planned MD’s area: $N_{\mu}^{MD} = 82.4$, $\sigma(N_{\mu}^{MD}) = 11.9$, $\frac{\sigma(N_{\mu}^{MD})}{N_{\mu}^{MD}} = 0.14$.](image)

It means one could make a large detector viewed by a single PMT and have enough light to register neutrons. In our case we have $\sim$ 50 photo-electrons from PMT photo-cathode. The efficiency of thermal neutron detection was found to be 20%. Pulse duration (the fastest component) is equal to $\sim$ 40 ns. Taking into account that heavy particles also excite slower component one can use this for pulse shape selection. The scintillator layer is very thin (30 $mg/cm^2$) so it is almost insensitive to single charged particles and gamma–rays, but it can be successfully used for EAS particle density measurements. The array’s response simulation will be performed in order to optimize the number of TND’s and their arrangement.
3. Carpet-3 performance capabilities

The EASs with axes well inside the Carpet will be analyzed. Due to large continuous area of the Carpet and relatively small areas of individual detectors the accuracy of axis position for such events is $\sim 0.2$ m. This gives a possibility to perform fine-resolution measurements of the lateral distribution function (LDF) and its fluctuations near the EAS core. For example, the measured LDF of the charged particles for $N_e \geq 2 \cdot 10^5 (N_e = 5 \cdot 10^5)$ and simulated ones are compared in Fig. 3. 

![Fig. 3. LDF of the charged particles in the Carpet experiment (points). Lines - simulation (CORSIKA, QGSJet01c + GHEISHA, [8]): 1 - primary protons, 2 - primary iron nuclei.](image)

The number of thermal neutrons, as a first approximation, is proportional to the total number of hadrons in EAS. The total number of hadrons, in turn, can be used as an energy estimator of a primary particle (Fig.4), and to this effect the total area and location of thermal neutron detectors (TND) will be optimized.

In addition to muons with $E_\mu > 1$ GeV, MD can also detect hadrons with $E_h \geq 30$ GeV. In the absorber above MD the EAS hadrons generate cascades producing energy deposit in the scintillator. The thickness of the absorber is equal to $\sim 20$ radiation lengths; it is enough to absorb electromagnetic component but not the hadronic cascades because of its having only $\sim 5$ hadron interaction lengths. The number of such hadrons can be taken as the number of cascades in MD, i.e., the number of spots with local density of $\geq 10$ particles per $m^2$ [10,12]. It is not only the number of hadrons in MD but their total energy as well that can be measured. For this purpose the TND’s will be placed under the scintillator detectors, in the underground tunnels, to measure the number of thermal neutrons. Because the number of thermal neutrons depends on energy of cascades, the total energy of hadrons in MD can be measured (the method of ionization-neutron calorimeter, developed for the INKA project [13]).

![Fig. 4. Dependence of mean number of hadrons with $E_h \geq 30$ MeV on energy of primary protons and iron nuclei (CORSIKA, QGSJet01c + GHEISHA, [8]).](image)

4. CONCLUSIONS

For each EAS will be measured, at least, 6 parameters:

1) $N^C_{ch}$ - the number of charged particles in Carpet;
2) $s^C$ - age parameter of NKG-function near the EAS axis;
3) $N^{ND}$ - the number of thermal neutrons in the surface TND’s;
4) $N^\mu$ - the number of muons ($E_\mu > 1$ GeV) in MD;
5) $N^{MD}$ - the number of hadrons ($E_h \geq 30$ MeV).
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GeV) in MD;
6) \( N_{n}^{ND} \) - the number of thermal neutrons in the underground TND’s.

Multiple parameter method is assumed to allow determination of both energy and atomic number of a primary particle with good enough accuracy.

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REFERENCES

1. V.S. Ptuskin and V.N. Zirakashvili, [astro-ph/0408025] (2004).
2. Kulikov G.V. and Khristiansen G.B., JEPT, 35, 635 (1958).
3. Gerd Shatz, Proc. 28 ICRC (Tsukuba), 1, 97 (2003)
4. Petrukhin A.A., Proc. Xth Rencontres de Blois "Frontiers of Matter", Blois, France,
ed. J.Tran Thanh Van, The Gioi Publishers, Vietnam, p.401 (2001).
5. Yu.V. Stenkin, Mod. Phys. Lett. A, 18, 1225 (2003).
6. A.P. Garyaka et al., arXiv: 0704.3200v1 [astro-ph]
7. H. Ulrich at al., Proc. 30 ICRC (Merida), 4, 87 (2008).
8. D. Heck et al., Report FZKA 6019 (1998), Forschungszentrum, Karlsruhe.
9. D.D. Dzhappuev et al., Bulletin of RAS: Physics, v.71, N 4, 525 (2007).
10. D.D. Dzhappuev et al., Proc. of the International Cosmic Ray Workshop Aragats 2007 (Nor-Amberd, Armenia, 8-13 September 2007), Edited by B.Pattison and R.Martirosov, Yerevan Physics Institute, p.102, 2007.
11. Yu.V. Stenkin et al., Proc. 30 ICRC (Merida, Mexico, 2007), Universidad Nacional Autonoma de Mexico, Mexico City, Mexico, 2008, V. 5, p. 1041.
12. D.D. Dzhappuev et al., Proc. 30 ICRC (Merida, Mexico, 2007), Universidad Nacional Autonoma de Mexico, Mexico City, Mexico, 2008, V. 4, p. 19.
13. K.V. Aleksandrov et al., Nucl. Phys. B (Proc. Suppl.), 122, 427 (2003).

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