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Multiplicity, yield and response functions for Baksan EAS-arrays and Muon Detector in comparison with similar functions of Neutron Monitors

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The EAS-arrays with using one-particle mode of registration appear to be more sensitive to solar cosmic rays (SCR) with energies above 5 GeV due to their larger effective area in comparison with that of standard Neutron Monitors (NMs). As was obtained earlier, the Baksan EAS-arrays (Andyrchy and Carpet) and the Baksan Muon Detector (BMD) at geomagnetic cutoff $P_C \approx 6$ GV have registered statistically significant increases in 50 % cases of the GLEs documented over data of NMs. Using of the combined data of three Baksan detectors and the worldwide network of NMs allows extending a spectrum of SCR into the energy interval of 5-10 GeV, where the data of NMs quite often are absent. The yield and response functions of Baksan detectors for one-particle mode of registration are necessary to reconstruct the primary SCR intensity by recorded counting rate of secondary particles. The results of calculation of these functions for all three Baksan detectors are represented. Comparison of the calculated functions for above detectors with corresponding functions of NMs was carried out.

1. Introduction

Existing worldwide network of Neutron Monitors (NMs) allows measuring of spectra of the Solar Cosmic Rays (SCR) in the majority of GLE events only up to 4-5 GeV. Exceptions are only huge events such as 23 February 1956 and 29 September 1989. Rather low efficiency of neutrons registration at NMs and, as a consequence, low counting rate of these detectors do not allow promoting in the range of higher energy. Devices with large geometric factor are necessary for studying high-energy part of SCR spectrum because the excess of SCR above a background of galactic cosmic rays (GCR) above 5 GeV is rather small. Therefore, we suggest in addition to the NMs data to use the information from existing non-standard detectors having the large sensitive areas. First of all, these are the detectors designed for registration of various EAS components.

Specified detectors have the large areas and high efficiencies for registration of electromagnetic, hadron and muon components of secondary cosmic rays (CR). However, energy of the primary particles causing large EAS, is extremely high (tens TeV and more) and on some orders of magnitude exceeds energy of reliable recorded SCR. So-called 2-, 3-, and n-fold triggers (coincidences of counters) are used for the EAS registration. For studying of SCR spectrum we suggest to use the counting rate of single particles (1-fold trigger) at the EAS-arrays and at the muon detectors with large area. In this case the range of sensitivity to primary energy will be close to known energy of SCR (from several GeV up to several tens of GeV). The counting rate of such detectors is hundreds times higher than that of NMs. It allows measuring ten times weaker CR flux. Thus, effective area of the standard module of the neutron monitor (6-NM-64) makes up 1.8 m^2, that provides average counting rate about 100 counts per second. For comparison, the Baksan EAS and muon detectors have following sensitive areas (the areas of scintillator): Andyrchy – 37 m^2, Carpet – 196 m^2, the Baksan Muon Detector (BMD) – 175 m^2, and their average counting rates are, respectively, 11000, 42000 and 19000 counts per second. While statistical accuracy of the standard neutron monitor by 5-minute data makes up about 1 %, for the Andyrchy, Carpet and BMD it makes up of 0.055 %, 0.03 % and 0.04 %, respectively.

The increases of SCR (GLE events) have been already observed by similar detectors earlier: the Baksan Carpet – on 29 September 1989 [1, 2], MILAGRITO – on 6 November 1997 [3], GRAND – on 15 April 2001 [4]. Also, the Andyrchy and Carpet have registered six GLEs of 23rd cycle of solar activity [5]. Further analysis of GLE events by the data of three Baksan detectors (Andyrchy, Carpet and BMD) has shown that increases of the SCR flux with energy above 5 GeV are observed nearly in 50% of specified events [6]. The analysis of the Baksan detectors data in a combination with the data of worldwide network of NMs allows extending spectra of SCR for various GLE events into the energy interval of 5-10 GeV [7, 8]. The data of NMs often are absent at that energy in majority of GLE events. The yield and response functions of the EAS-arrays and the muon detector for one-particle mode of registration are necessary for similar analysis.

2. Description of Method and Detectors

All detectors of cosmic rays located at the Earth's surface register secondary cosmic rays. Therefore, to obtain the primary SCR spectra we need to do reverse transformation from the recorded counting rate of specified detector to the primary SCR intensity. The multiplicity functions of the secondary particles generation, yield and response functions of detectors for the one-particle mode of registration of various secondary components are necessary for similar analysis. These functions have been calculated for the Andyrchy, Carpet and BMD, and they are represented in this work. All three detectors are located in Baksan valley on North Caucasus (geographical coordinates are 43.28°N, 42.69°E). The effective vertical geomagnetic cutoff rigidity P_C is about 5.7 GV (according to Tsyganenko-1989 model of magnetosphere).

Passage of particles through the atmosphere up to the level of Baksan detectors was modeled with the well-known software package CORSIKA (v.6.031, QGSJET) [9]. The depth in the atmosphere for the Carpet and BMD is 835 g/cm^2 (1700 m above see level) and the depth for the Andyrchy is 800 g/cm^2 (2050 m a.s.l.). Calculations were carried out for the primary protons. We did not take into account the nuclei with Z >1 because their fraction in the SCR is rather small at energy >1 GeV. The yield and response functions for vertical flux of the primary CR are used usually in analysis of the NMs data. Therefore, we also calculated above functions for vertical flux only. As a result, we have obtained multiplicity functions of the secondary particles generation at the Baksan level versus of primary energy.

The vertical differential response and specific yield function are related as follows [10]:

$$\frac{dN(p,x,t)}{dp} = S(p,x)\cdot\frac{dJ(p,t)}{dp} \qquad (1)$$

where $dN(p, x, t)/dp$ is the contribution to the counting rate of the detector located at depth x at the time t from primary particles with rigidity of p to $p + dp$ arriving within a small solid angle near the vertical direction; $S(p, x)$ is a Specific Yield Function (SYF) of detector for primary particles; and $dJ(p, t)/dp$ is the primary cosmic ray spectrum.

To obtain the yield functions, the processes of particles registration in Baksan detectors were simulated by Monte Carlo method with using of authors' programs. The real configuration of arrays and the construction of their separate counters were taken into account. The Andyrchy consists of 37 counters constructed from plastic scintillator with area of 1×1 m^2 and with thickness of 5 cm. A distance between the detectors is 40 m. The average amount of structural materials above scintillator is 4.5 g/cm^2. The Baksan detector Carpet is a central part of EAS-array. It consists of 400 counters made on the basis of liquid scintillator with a volume of 70×70×30 cm^3. The counters cover the area of 14×14 m^2 with a continuous layer. The Carpet is located in a building under the concrete roof with a thickness equal to 21 g/cm^2. The counting rate of both EAS-arrays is composed of hard component (high energy muons and hadrons; ≈55 % of counts for the Andyrchy and ≈70 % for the Carpet) and soft component (low energy muons, hadrons and electromagnetic component,

≈45 % and ≈30 % of counts, respectively). The BMD consists of 175 counters quite similar to the Andyrchy ones. The depth of BMD location is of 6 m.w.e., and it registers muons with threshold energy ≥1.2 GeV that corresponds to minimal losses of energy in the ground. The threshold energy of registration for each counter of all three Baksan detectors is about 0.5 of the most probable energy losses of a single relativistic particle.

3. Results of Calculations

The calculations of SYF give rather correctly an energy dependence of the detector response. However, they do not guarantee absolute value of the SYF. Therefore, the SYF for each Baksan detector have been normalized on the average counting rate. With this purpose, the differential response functions have been obtained with Eq. (1) after multiplication the SYF by the galactic CR spectrum [11]. The integral of this function from P_C to infinity represents total counting rate of the detector. The normalizing factors have been derived from comparison of above integral with the real counting rate of each detector. This method is quite similar to the normalizing of the SYF for neutron monitor [10].

The normalized SYFs for the Andyrchy, Carpet and BMD are depicted at the left panel of Figure 1. For comparison, the SYF of NM [12] is also represented in Figure 1. As seen from this Figure, the SYFs of EAS-arrays and muon detector are of some orders of magnitude higher than that of the NM at rigidities exceeding the geomagnetic cutoff at Baksan. This provides considerably higher counting rate and better sensitivity of the Baksan detectors to SCR with energy above 5 GeV. At the same time, the NM is more effective at smaller rigidities.

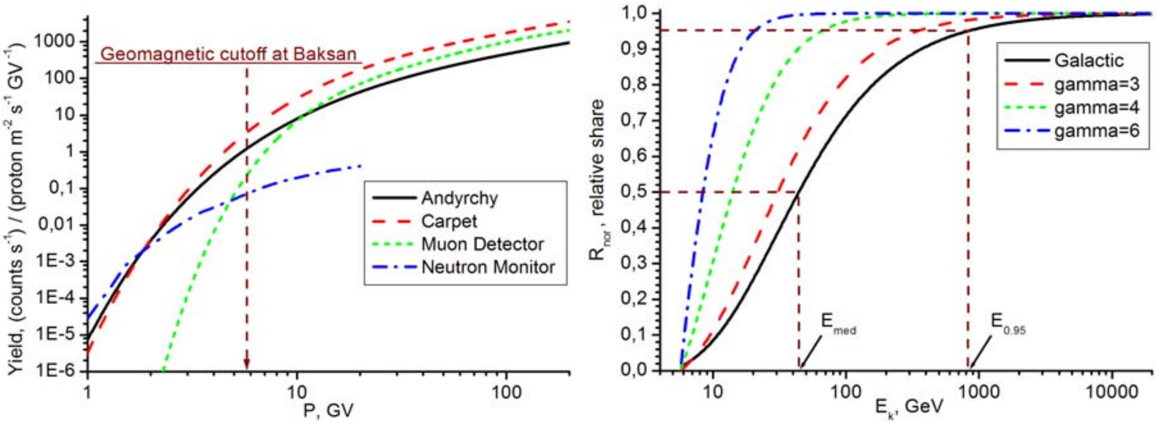

Figure 1. The main results of calculations. Left panel: the specific yield functions of various Baksan detectors (the Andyrchy, Carpet, BMD and Neutron Monitor). Right panel illustrates the normalized response functions of the Andyrchy for various primary spectra and definition of the E_{med} and $E_{0.95}$.

For a description of energy range in which the Baksan detectors are most sensitive, the median energy E_{med} (50% of particles have energy $<E_{med}$, and as much particles $>E_{med}$) and the top border of sensitivity range $E_{0.95}$ (95% of particles have energy in a range from the cutoff up to $E_{0.95}$) have been estimated. These values are defined with use of the normalized integral response function R_{nor} (E) that is shown at the right panel of Figure 1. The specified energies strongly depend on the shape of a primary spectrum. The SCR spectra in GLE events usually have considerably steeper slope than the GCR spectrum. Therefore, the energy range of detectors' sensitivity will be different during the registration of SCR. The R_{nor} (E), E_{med} and $E_{0.95}$ have been calculated for the GCR spectrum and for some spectra with slopes typical for the SCR. The R_{nor} (E) of the

Andyrchy for the spectra with various power-law indices is also shown at the right panel of Figure 1. The values E_{med} and $E_{0.95}$ for different spectra are represented in Table 1.

Table 1. The energies E_{med} and $E_{0.95}$ for various kinds of primary spectra

Spectrum:	Galactic		Power, $\gamma = 3$		Power, $\gamma = 4$		Power, $\gamma = 6$	
Energy (in GeV):	E_{med}	$E_{0.95}$	E_{med}	$E_{0.95}$	E_{med}	$E_{0.95}$	E_{med}	$E_{0.95}$
Andyrchy	44	810	31	340	14	65	8.4	20
Carpet	45	740	32	310	17	67	9.7	24
BMD	51	510	40	280	23	83	13	32
Baksan NM	14	190	12	92	8.1	27	6.3	13

The comparison of values of Table 1 shows that the median energy and the sensitivity range strongly depend on the shape of a primary spectrum. Also, the corresponding estimates differ visibly for various detectors.

4. Conclusions

The yield and response functions have been calculated for three Baksan detectors: the Andyrchy, Carpet and BMD. These functions are greatly needed to determine SCR spectra of GLE events above the energies of 5 GeV. The comparison of the functions obtained for EAS-arrays, muon detector and neutron monitors was carried out. The Baksan detectors are appear to be more sensitive to SCR with energy above 5 GeV in comparison with NMs. Also, the median energy and sensitivity range of EAS-arrays and muon detector strongly depend on the form of a primary spectrum. They are considerably higher than that for NMs.

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