YEREVAN STATE UNIVERSITY
PHYSICS FACULTY

MASTER THESIS

ESTIMATION OF THE ENERGY THRESHOLD OF NAMMM AND SEVAN PARTICLE DETECTORS

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YEREVAN - 2008

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Introduction

High energy particles, accelerated on the Sun (Solar Cosmic Rays – SCR) are superimposed on the Galactic Cosmic Ray (GCR) background. Cosmic Rays have the most direct impact on humans in space, on space-based electronics and on other important technological assets. The other source of the variability of cosmic ray flux are huge magnetized clouds (Coronal mass ejections – CMEs), emitted by sun and traveling in the Interplanetary Space (IP). This gigantic plasma clouds with "frozen" magnetic field disturb the Interplanetary Magnetic Field (IMF). The SCRs arrive at earth from in time from 10 minutes till many hours due to particle energy dependent diffusion. The intensity of radiation in near earth environments can boost thousand times in few minutes posing serious hazard to space operations and over-polar flights. Therefore, continuous monitoring of the particle fluxes is of crucial importance for alerting on radiation hazard. Because only highest energy cosmic rays can generate particle cascades reaching at the Earth surface (and triggered Ground Level Enhancements – GLE) the information of upcoming abundant low and middle energy cosmic rays can be ascribed from the enhancements of the time series of count rays of surface particle monitors. On the other hand the same time series contain information on the disturbances of the IP magnetic field and may prove useful for the forecasting of the severity of geomagnetic storm unleashed by at the arrival of ICME. Size and magnetic field of IP CMEs (ICMEs) are correlated with the modulation effects the ICME poses on the ambient population of the galactic cosmic rays during its propagation up to 1 AU. On the way to Earth (15 – 50 hours) the magnetic cloud and shock modulate the GCR flux, changing its intensity and making it anisotropic. The strength of these modulation effects correlate with geomagnetic indices of the storm unleashed on arrival of the ICME to the magnetosphere.

Space-borne spectrometers measure the time series of the changing fluxes with excellent energy and charge resolution. Surface detectors measure time series of secondary particles born in cascades originated in the atmosphere by primary ions and solar neutrons. Networks of the particle detectors located on Earth surface can detect these modulation effects predict the upcoming geomagnetic storms hours before the ICME arrival at the magnetometers on ACE and SOHO. The half-hour lead time (time span ICME travels from space stations to magnetosphere) provided by the particle detectors located at the space stations ACE and SOHO 1,5 million kilometers from the Earth is a bit short to take effective mitigation actions and protect satellites and surface industries from harm of major geomagnetic storms.

To establish reliable and timely forecasting service we need to measure, simulate and compare:

- time series of neutrons, the low energy charged component (mostly electrons and muons) and the high energy muons;
- the correlations between changing fluxes of various secondary particles; and
- direction of the detected solar cosmic rays.

Surface monitors located at the Aragats Space Environmental Center (ASEC) at 2000 and 3200 m altitudes (40˚25′N, 44˚15′E; Vertical cut-off rigidity in 2007: 7.1 GV) detect charged and neutral components of the secondary cosmic rays with different energy thresholds and various angles of incidence.

Part One: Estimation of the threshold energy of NAMMM

The Nor Amberd multidirectional muon monitor (NAMMM, see Figure 1) is in operation by Cosmic Ray Division (CRD) at Nor Amberd research station of the Alikhanyan Physics Institute. NAMMM located on the slope of the mountain Aragats at 2000m above sea level. Geographical coordinates are 40°22'N, 44°15'E.

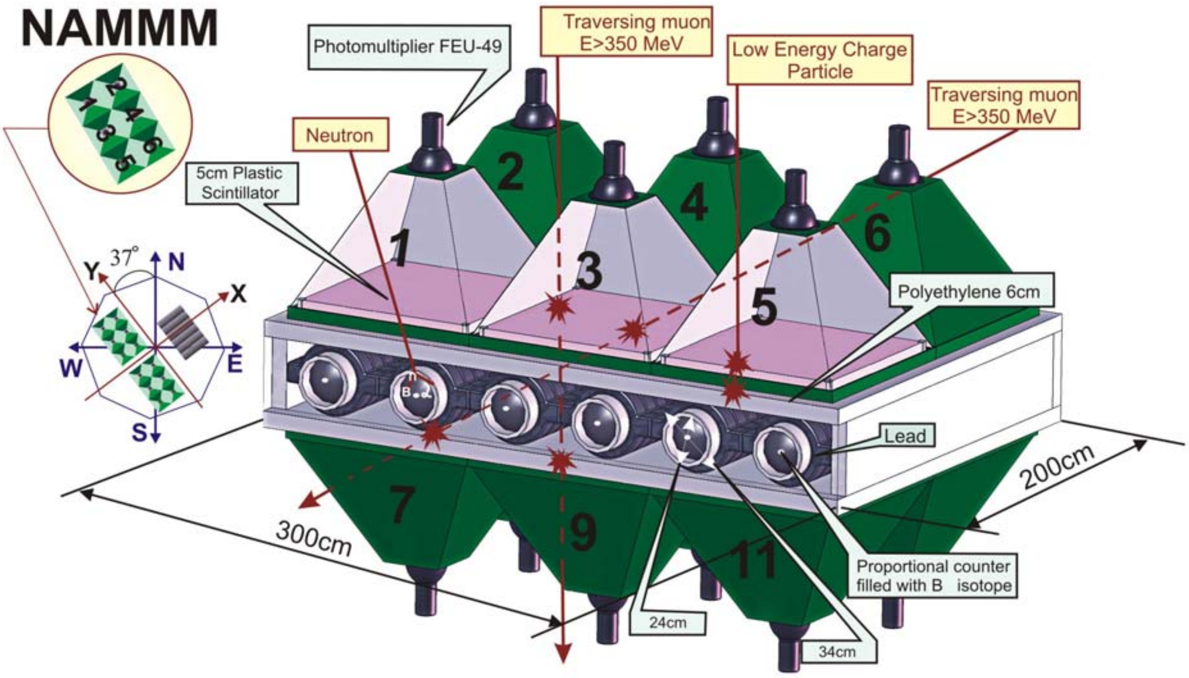


Figure 1. Nor Amberd multidirectional muon monitor (NAMMM).

Detector consists of two layers of plastic scintillators above and below two of the three sections of the Nor Amberd Neutron Monitor 18 NM64/ The lead (Pb) filter of NM absorbs electrons and low energy muons. The distance between layers is approximately 1 m. Each layer consists of six detectors, each having the area of 0.8 m^2. The data acquisition system of the NAMMM can register all coincidences of detector signals from upper and lower layers, thus, enabling measurements of the arrival of the muons from different directions.

In Figure 2 the blue curve demonstrates the angular frequency histogram of muons incident the upper layer of detector. In the same Figure by red color is denoted analogical frequency histogram of muons traversing the scintillator in the lower layer just below the upper one.

An example of such event is depicted in Figure 1.

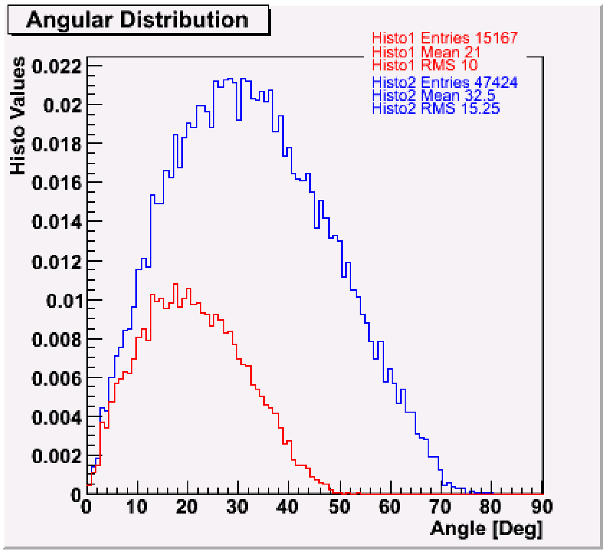


Figure 2. Angular frequency histograms of muons registered by upper detector of NAMMM (in blue), and – by coincidence of upper and lower detectors(in red).

NAMMM is hybrid detector measuring neutral and charged CR fluxes. Upper layer of detector measures low energy charged particles, mostly electrons and muons. The energy threshold is of the upper scintillators is determined by the sensitivity of photomultiplier PM and data acquisition electronics (DAQ) and is equal ~7 MeV.

Neutron monitor is measuring the secondary neutrons of the cosmic ray flux. The lower layer of the scintillators of NAMMM is sensitive to high energy muons, because low energy muons and electrons are absorbed by the 10 cm lead filter.

Detecting Ground Level Enhancements by different monitors, sensitive to various energetic populations of the primary solar particles it will be possible to reconstruct energy spectra of GLE and determine the spectral index. The large energy spectral index of the SCRs at highest energies ($\gamma \geq -5$, hard spectra; usually SCR spectra is very steep at GeV energies: $\gamma \leq -7$) is a very good indicator of upcoming abundant SCR protons and ions with energies >50 MeV, extremely dangerous for the astronauts and high over-polar flights, as well as for satellite electronics.

It is way it is important to know the energy threshold of the lower layer of NAMMM. From the known threshold energy of the secondary muons detected by the NAMMM we'll reconstruct the most probable energy of the primary solar protons giving rise to the GLE. Along with similar data from neutron monitor and upper layer of the NAMMM will have enough information to calculate the spectral index of the GLE in progress and warn space operators if estimated value of index is greater than –5.

We estimate the threshold energy using 3 different methods:

- by calculation of ionization losses of muons in lead;
- by computer simulation of particle cascade development in atmosphere and response of monitor to the secondary cascade particles;
- by comparing simulated spectrum and experimentally measured detector count rate.

Calculation of energy losses of muons in lead

Moderately relativistic charged particles ($\beta\gamma < 1000$) other than electrons lose energy in matter primarily by ionization and atomic excitation. The mean rate of energy loss is given by the Bethe-Bloch equation,

$$-\frac{dE}{dx} = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2}{I} - \beta^2 - \frac{\delta}{2} \right], \qquad (1)$$

$$\beta = v/c, \qquad \gamma = (1-\beta^2)^{-1/2}, \qquad K = 4\pi N_A r_e^2 m_e c^2 .$$

Here $K = 0.307075$ MeV cm^2, z is the charge of incident particle, Z-atomic number of absorber, A - atomic mass of absorber in g mol^{-1}, $m_e c^2$-the rest energy of electron, $I = 16Z^{0.9}$ is the mean excitation energy. δ is the density effect correction to ionization energy loss. In our calculationswe will not take into account this effect.

By integrating equation (1) we can obtain total energy release of muon before reaching the lower scintillator, which coincides with energy threshold of NAMMM.

Right hand part of Bethe-Bloch equation contains quantities, which are not depend on path length x explicitly. That's why we cannot integrate Eq. (1) on x directly and find function E(x). But since right hand part of eq.(1) depends on β, which determines explicitly kinetic energy E, the inverse function *dx/dE* can be immediately integrated:

$$R = -\int_{E_f}^{E_{in}} \frac{dE}{dE/dx} \qquad (2)$$

Here R represents integral path (or simply path length) of the particle. E_{in} is the initial energy of muon and E_f is its final energy.

Using muon kinetic energy $E = Mc^2/(1-\beta^2) - Mc^2$, we find $dE = M\,v\,dv/(1-\beta^2)^{3/2}$. Substituting the found dE and dE/dx from Eq (1) into (2) and neglecting δ we will obtain the following expression:

$$R = C\int_{\beta^2_f}^{\beta^2_{in}} \frac{\beta^2 d\beta^2}{(1-\beta^2)^{3/2}\left(\ln\frac{k\beta^2}{1-\beta^2} - \beta^2\right)}, \qquad (3)$$

$$C = \frac{A}{(Kz^2Z)}Mc^2, \qquad k = \frac{2m_e c^2}{I}.$$

Here *C* and *k* are constants. From this expression we can get the threshold energy of NAMMM. *R* is the path length in g/cm^2. If we want to get value in cm-s, we should divide *R* on the density of absorber. Path length is fixed by the geometry of detector and by angle of incidence. There is about 10 cm of lead between upper and bottom layers of NAMMM. For Pb the numerical values of the constants C and *k* come to C=430 g/cm^2 and k=1200. But we should take into account that scintillators are registering particles with energies >7MeV. Thus we need to know the energy of incident muon, which can penetrate through 10 cm of lead and still have residual energy equal to 7 MeV. We have calculated integral in Eq. (3) numerically by using Simpson's method [1] . In this method integration results in calculating of sum by using following extrapolating formula:

$$I = \int_a^b f(x)dx = \frac{h}{3}(y_0+4y_1+2y_2+4y_3+2y_4+\ldots+2y_{n-2}+4y_{n-1}+y_n), \qquad (4)$$

where y_i are values of function f(x) in discrete points x_i: $y_i = f(x_i)$, $i=0,1,\ldots,n$; $h = x_{i+1} - x_i$

In Simpson's method error of calculation is minimal for n = 50…100. Relative error is less than 0.01%. We have calculated integral in (3) for n=50 and 100 for various values of β_{in} and fixed β_f corresponding to 7MeV. Thus we found the value of β_{in} for Eq.(3) at R=10 cm. The found β_{in}^2 = 0.87 gives for this case the value of E_{thresh}=187MeV. The value of integral (4) in this case was equal to 0.266. These calculations have been performed with using standard Mathematica 5.0 program.

Estimation of the energy threshold of NAMMM using computer simulation

The second method of energy threshold estimation is based on computer simulation of passing primary particles through Earth atmosphere and NAMMM. The simulations are performed using GEANT 3 package. We simulate particle cascade development in atmosphere and response of NAMMM to the secondary cascade particles. Thus we have the energy spectrum of secondary particles at 2000m above sea level.

In Figure 3 we can see the frequency histogram of energies of muons registered by the lower detector of NAMMM (we put a limit on the maximal energy of 500MeV); secondary muons usually have energy above 200 MeV. This picture can be easily obtained from Tbrowser of Root package [2].

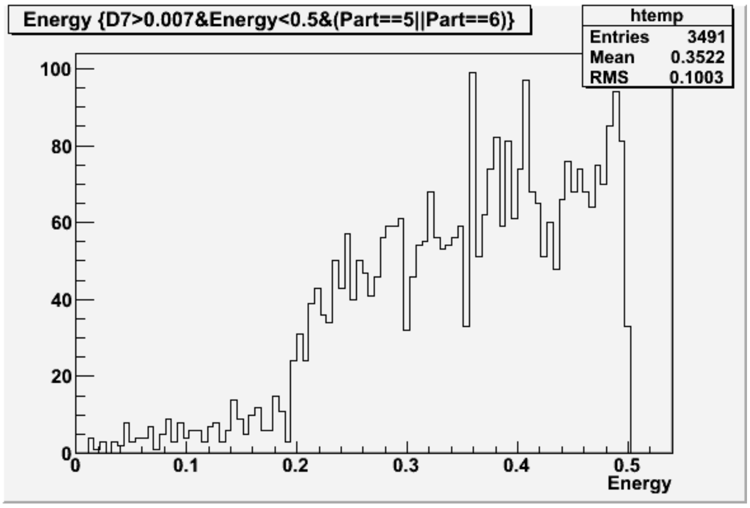


Figure 3. Events registered by the lower layer of NAMMM with energies<500MeV

Fitting of muon spectrum function was performed by power. The result is shown in Figure 3.

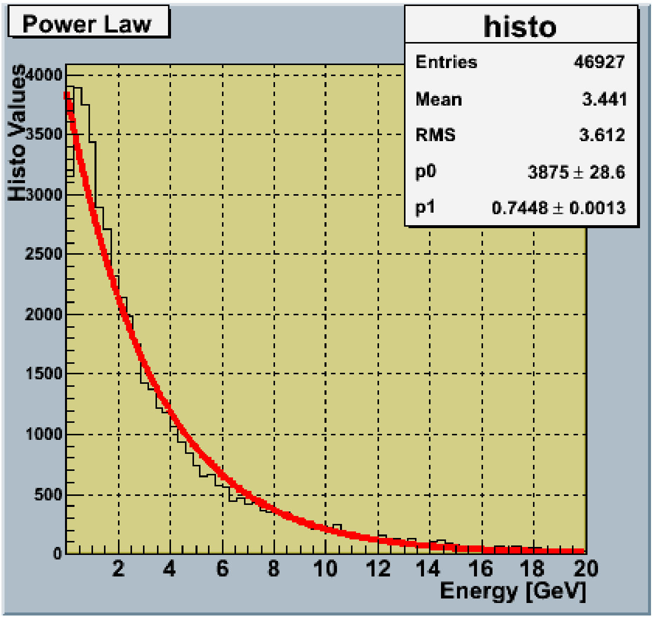


Figure 4. Fitting the spectrum of muons at 2000m above sea level

To obtain the energy threshold of NAMMM, we should calculate the lower limit of the following integral

$$\int_{E_{tresh}}^{20} p0 \cdot p1^{E}\, dE = \tfrac{2}{7} N \qquad (5)$$

Note, that before we tried to fit the spectrum by power function $E^{-\gamma}$, but results were worse than in the case of b^{E}, i.e. fit function wasn't correspond to histogram and big part of histogram points were far from fit function curve.

Here p0=3875, p1=0.7448 are parameters of fit, N is the count rate per 5 min, which coincides with histogram entries in Figure 4. We multiply count rate by 2/7 since there are 7 histogram bins in the range of 2GeV energy. Because the value of the integral (5) equals to the area of histogram. And the area of this histogram is equal to number of bins in histogram.

According to simulated data count rate of NAMMM is equal to N=44176 for 5 minutes (Simulations were performed for 5 min. to provide statistics) and the energy threshold is correspondingly equal to 140MeV.

The underlying cause of such a small value is the bad fit, especially in the region up to 2 GeV.

Experimental data from NAMMM

Now let's compare experimental and simulated data. I have used the data of NAMMM from September 15 to 30 of 2006 (that period of time was taken, because detector worked properly at that time), according to which the lower detectors of NAMMM have registered in average 8700 particles per minute per 0.81m^2 (Each detector surface area is 0.81 m^2). When placing this value in equation 5 instead of N we will get for threshold energy the value E = 200MeV. This value obtained from experiment is higher than the modeled value of 140MeV. Such a discrepancy is apparently due to 16cm polyethylene layer not taken into consideration in the model. Due to this layer some particles with relatively low energy (about 190 MeV) can't traverse through this two layers of scintillators and the energy threshold will be higher).

Besides we have not taken into account at the sides of NAMMM the low energy particles, which may be registered in the lower detector. Due to that the energy threshold is smaller.

Comparison of the three methods

So we found three different estimations for the threshold energy:

- 187 MeV from Bethe-Bloch equation
- 140 MeV from simulated data
- 200 MeV from superimposing simulated and experimental data

To obtain more precise value of threshold energy in our simulations and calculations we should take into account polyethylene layer of 16 cm, which will give increasing in the calculated energy threshold.

In further we are also going to take into account low energy particles falling to the sides of NAMMM, which may be registered in the lower detector.

Contribution of polyethylene layer in the threshold

As we said, the difference between simulated and experimental results could be explained by the existence of polyethylene 8cm layers, which we didn't take into account. The difference should be about 60 MeV.

Muons passing upper layer should have enough energy to reach bottom scintillator layer. And here can be used the approximate formula for ionization loses of relativistic particles in the light matter (A/Z=2).

So we will get 16 MeV for the upper polyethylene layer.

Energy loses in the lower polyethylene layer are calculated using Bethe-Bloch equation as described above. Here approximate formula can't be used, because muons already passed 8cm polyethylene and 10cm lead and they can have small energies. Consequently energy loses could be much higher.

For polyethylene constants are C=600 g/cm^2 and K=21000 correspondingly. And the energy loses in the bottom detector is about 44MeV.

So 60MeV should be added to the result of the first method. The energy threshold will be 248 MeV.

Conclusion

By comparing different methods of estimation it's obtained about 250 MeV for the threshold energy.

Estimation of the energy threshold of SEVAN particle detector

Introduction

We designed and fabricated a new-type of particle detector to meet the above goals. In order to keep the instruments inexpensive, the options
are kept flexible by using modular designs. The price of a fully autonomous basic detector, with the facility to send data to the Internet will not exceed $20 000 U.S. For this reason the network of countries involved in space research can be significantly expanded, which will facilitate their part in the International Heliophysical Year-2007 (IHY-2007).

At any time one can add additional similar units to achieve improved functionality: for example, one could add several new observational directions and enhance the accuracy of particle fluxes measurements. As a world-wide network of neutron monitors, the new monitors will measure neutron fluxes and, additionally, charged particle fluxes with different energy thresholds, thus allowing one to investigate the additional populations of primary ions.

These units plan to be deployed at universities and research centers of developing countries to perform survey and monitoring of the most dangerous space storms and to involve new generations of students and scientists in space research.

The network is planned to be installed at middle and low latitudes. It will be compatible with the currently operating high-latitude neutron monitors network "Spaceship Earth", coordinated by the Bartol Research Center, with the Solar Neutron Telescopes network coordinated by the

Nagoya University, with the Muon network coordinated by the group from Shinshu University and with the Athens Neutron Monitor Data Processing Center.

The potential recipients of particle detectors in this new initiative are Croatia, Slovakia, Costa Rica, Bulgaria, Indonesia, and India (see Table1). When fully deployed the SEVAN network will provide the reliable monitoring of the Sun by a minimum of one detector for 22 h and by 2 detectors for 18 h of a day. We assume that particle fluxes measured by the new network at medium to low latitudes, combined with information from satellites and particle detector networks at high latitudes will provide experimental evidence on the most energetic processes in the solar system and will constitute an important element of the global space weather monitoring and forecasting service.

SEVAN particle detector's description

The basic detecting unit of the SEVAN network (see Fig. 5) is assembled from standard slabs of 50×50×5 cm3 plastic scintillators. Between 2 identical assemblies of 100×100×5 cm3 scintillators (four standard slabs) are located two 100×100×5 cm3 lead absorbers and a thick 50×50×25 cm3 scintillator assembly (5 standard slabs). A scintillator light capture cone and Photo Multiplier Tube (PMT) are located on the top and bottom, as well as in the intermediate layers of the detector. The detailed detector charts with all sizes are available from crdlx5.yerphi.am

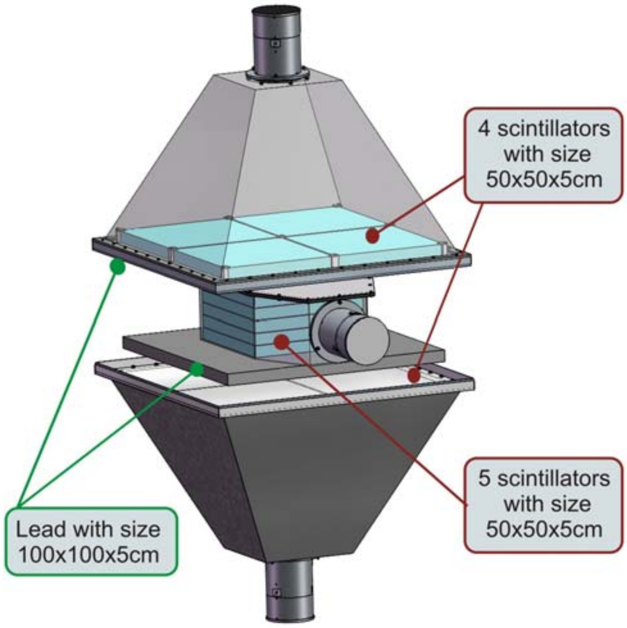


Fig.5 The basic detecting unit of the SEVAN network

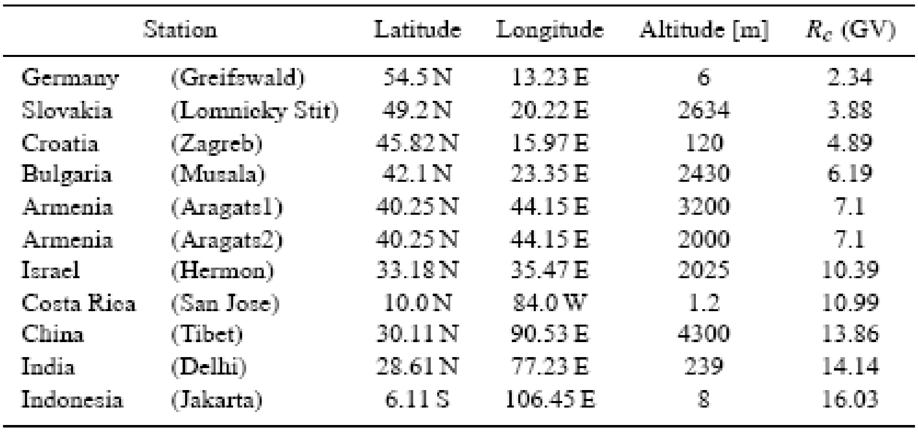
Incoming neutral particles undergo nuclear reactions in the thick 25-cm plastic scintillator and produce protons and other charged particles. In the upper 5-cm thick scintillator charged particles are registered very effectively; however, for the nuclear interactions of neutral particles there is not enough substance. When a neutral particle traverses the top thin (5 cm) scintillator, usually no signal is produced. The absence of the signal in the upper scintillators, coinciding with the signal in the middle scintillator, points to neutral particle detection. The coincidence of signals from the top and bottom scintillators indicates the traversal of high energy muons. Lead absorbers improve the efficiency of the neutral flux detection and filtered low energy charged particles. If we denote by “1” the signal from the scintillator and by “0” the absence of the signal, the following combinations of the 3-layered detector output are possible:

- 111 – traversal of high energy muon;
- 011 and 010 – traversal of the neutral particle;
- 100 – traversal of low energy charged particle stopped in the scintillator or in the first lead absorber.
- 110 – traversal of higher energy charged particle stopped in the second lead absorber.
- 001 – registration of the inclined charged particles.

Microcontroller-based Data Acquisition (DAQ) electronics and Advanced Data Analysis System (ADAS) provide registration and storage of all logical combinations of the detector signals for further offline analysis and for online alerts. The slow control system, as on the ADAS subsystem, provides the remote control of the PMT high voltage and the important parameters of the DAQ electronics.

To quantify statements about the detection of different types of particles by the SEVAN modules, we need to perform detailed simulation of the detector response. We use simulated cascades of the charged and neutral secondary particles obtained with the CORSIKA (version 6.204) Monte Carlo code. The threshold energies for the primary particles assumed as input for CORSIKA correspond to the vertical cutoff rigidity of the detector locations . All secondary particles were tracked until their energy dropped below the predetermined value (50MeV for hadrons, 10MeV for muons and 6 MeV for electrons and photons) or reached all the way to the ground level. The spectra of primary protons and helium nuclei (99% of the flux at energies up to 100 GeV) are selected to follow the proton and helium spectra reported by the CAPRICE98 balloon-borne experiment.

Table 1. Geophysical characteristics of possible SEVAN sites



Station		Latitude	Longitude	Altitude [m]	R_c (GV)
Germany	(Greifswald)	54.5 N	13.23 E	6	2.34
Slovakia	(Lomnicky Stit)	49.2 N	20.22 E	2634	3.88
Croatia	(Zagreb)	45.82 N	15.97 E	120	4.89
Bulgaria	(Musala)	42.1 N	23.35 E	2430	6.19
Armenia	(Aragats1)	40.25 N	44.15 E	3200	7.1
Armenia	(Aragats2)	40.25 N	44.15 E	2000	7.1
Israel	(Hermon)	33.18 N	35.47 E	2025	10.39
Costa Rica	(San Jose)	10.0 N	84.0 W	1.2	10.99
China	(Tibet)	30.11 N	90.53 E	4300	13.86
India	(Delhi)	28.61 N	77.23 E	239	14.14
Indonesia	(Jakarta)	6.11 S	106.45 E	8	16.03

Calculation of the energy threshold of SEVAN particle detector

The efficiency of the charged particle detection by all 3 layers of the SEVAN detector is about 95%; the neutron detection efficiency in the middle “thick” scintillator reaches 30% at 200 MeV, the efficiency of the -quanta detection reaches 60% at the same energies. The lead absorbers filter low energy electrons and gammas. Figure shows that the lower layer is sensitive to the high energy muon flux with the threshold energy approximately 250MeV.

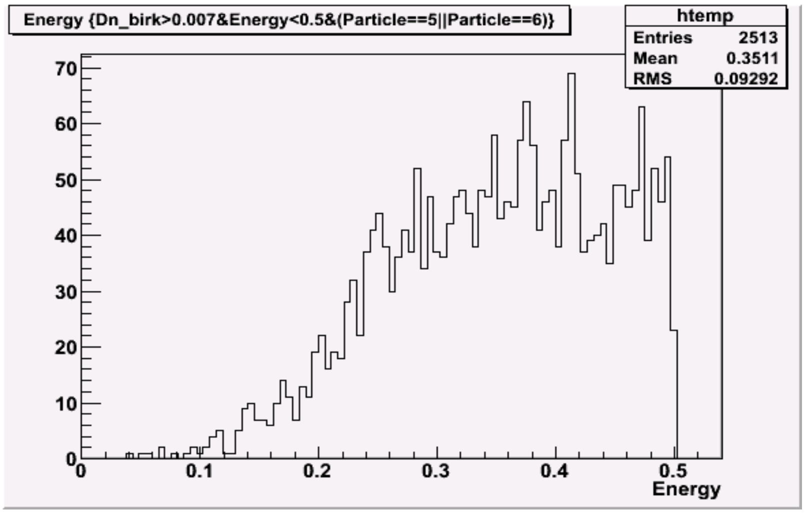


Fig.6 The energy threshold of basic detecting unit of the SEVAN network according simulation

Energy threshold also calculated using Bethe-Bloch equation. The result is the same 250 MeV.

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