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The OLVE-HERO calorimeter prototype beam test at CERN SPS

Ya.Sagan [1]

1. *Joint Institute for Nuclear Research*
   Joliot-Curie, 6, Dubna, Moscow region, 141980
2. *Dubna State University*
   University str., 19, Bld.1 Moscow region, 141980 Russia

E-mail: `yaroslav_sagan@mail.ru`

V. M. Grebenyk[1,2], **A. V. Krasnoperov**[1], **A. Pan**[1.3], **S. Yu. Porokhovoy**[1], **A. D. Rogov**[1], **A. B. Sadovsky**[1], **I. Satyshev**[1,3], **M. Slunecka**[1], **L. G. Tkachev**[1]

1. *Joint Institute for Nuclear Research,*
   Joliot-Curie, 6, Dubna, Moscow region, 141980
2. *Dubna State University,*
   University str., 19, Bld.1 Moscow region, 141980 Russia
3. *The Institute of Nuclear Physics*
   Almaty,050032 Kazakhstan

E-mail: `greben@jinr.ru`

D. M. Karmanov, **D. M. Podorozhny**

Skobeltsyn Institute of Nuclear Physics
Moscow State University, Moscow,

E-mail: `karmanov68@mail.ru`

A project of the OLVE-HERO space detector for measurement of the cosmic rays in the range 10^{12}-10^{16} eV is proposed. It will include a large ionization-neutron 3D calorimeter with a high granularity and geometric factor of ~16 $m^2 \cdot sr$. The main OLVE-HERO detector is expected to be an image calorimeter with boron loaded plastic scintillator and a tungsten absorber. Such a calorimeter allows to measure an additional neutron signal that should improve the detector energy resolution and also the rejection power between electromagnetic and nuclear components of cosmic rays. Improvement by factor 30-50 is expected. The OLVE-HERO detector prototype was designed and tested at SPS CERN beam during Pb ion run in 2018. Test results and the corresponding Monte-Carlo simulation are presented.

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1. Introduction

For study of the mechanism of acceleration and propagation of cosmic rays (CR) is very important the energy range of 10^{14} -10^{16} eV, the classical "knee" of the galactic CR. There are no direct measurements of the nuclei spectra in the "knee" CR area. Basic information about CR nuclei flux in the area before "knee" (10^{12} -10^{14} eV) was obtained in the balloon ATIC [1,2], CREAM [3,4], TRACER[5] and on satellites NUCLEON [6], AMS02 [7,8] and PAMELA [9] experiments. Nowadays have been started researches of CR in satellite experiments CALET [10] and DAMPE [11].

To learn out more of a near CR source we need to determine the spectrum of high-energy electrons (> 10^{10} eV) and its possible anisotropy. Extension of the CR secondary components spectra, i. e. of nuclei (Li, Be, B, sub-Fe etc.), by two orders of energy will make possible to research the processes of CR propagation in the Galaxy in detail.

Within the framework of the Russian Federal Space Research Programme it is expected to create the High-Energy Rays Observatory (OLVE - HERO) for the research of cosmic radiation in the energy range of 10^{10} -10^{16} eV. The main parameters of high-energy cosmic radiation are the type of particle, the value of its kinetic energy and the arrival direction. Therefore the proposed design of the OLVE-HERO detector is based on the development of a heavy (~10 t) ionization-neutron 3D image calorimeter with a geometric factor (~16 $m^2 \cdot sr$). In this scintillation-tungsten image calorimeter borated scintillator will be used. This will make possible to measure an additional signal from delayed thermal neutrons that would improve the energy resolution of the calorimeter, and, most importantly, increase 30-50 times the level of rejection between the electromagnetic and hadron-nuclear components of CR in whole energy range [12]. The first simplified OLVE-HERO prototype was already tested at SPS CERN in 2016 and 2017 and obtained results were published [13].

1.1 OLVE-HERO prototype

For the purpose of the experimental investigation of the neutron deceleration effects up to thermal energies, a prototype of the detector was designed and produced. Its schematic view is presented on Figure 1. OLVE-HERO prototype was made to study the rejections capability between the electromagnetic and hadron CR components in beam test experiments. The prototype consisted of 3 layers of silicon detectors of the charge measurement system (CMS) to define beam particles, forward T1 and backward T2 triggers and eight plates of borated scintillator (BS) size of 120x100x5 mm^3, that were located around lateral sides of calorimeter with 10 mm plastic moderator plates in between. For T2 trigger was used a calorimeter of shashlyk type consisting of 109 layers of 1.5 mm plastic scintillator plates and 0.8 mm tungsten converters of total size 120x120x240 mm^3 and ~15 radiation lengths with one PMT H8711-10 HAMAMATSU readout. All components with the exception of CMS were placed in a light-tight metal container.

In Figure 2 is presented the photo of two detecting planes of the borated scintillator: into 5 mm scintillator plane were cut grooves in every of those 1 mm WLS KURARAY fiber was pasted. Signals from fibers were gathered up to the collector and passed on the photocathode of 16-channel PMT type H8711-10 HAMAMATSU. The far end of the fiber was polished and covered by silver to reflect the light signal. The signal of the last PMT dynode was used to record amplitudes of events selected by a trigger.

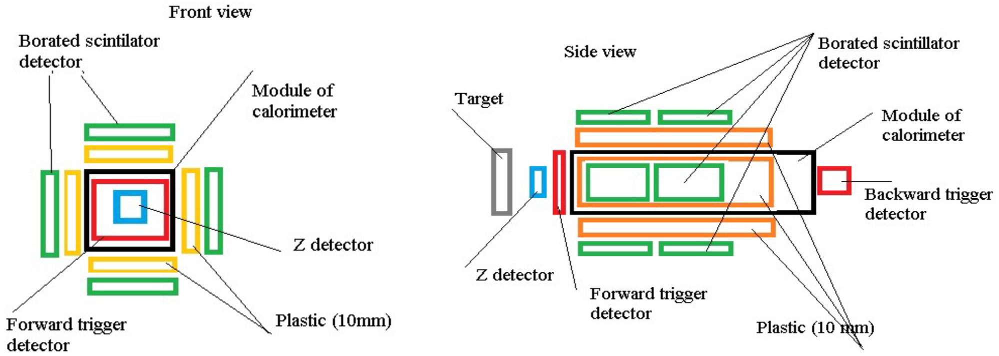

Figure 1. OLVE-HERO prototype scheme on the beam test experiment at SPS CERN

Neutron detection is useful because signal caused by neutron interaction with a detector matter occurs with a delay only in one of the planes and can therefore be clearly recognized. This is distinctive to the signal of charged secondary particles which give simultaneous non-delayed counts in all planes of the detector.

Evaporation neutrons produced in the target go through to the calorimeter that is working as a moderator and after slowing down to thermal energies are registered in borated detecting planes. However, neutron signal occurs only in case if a neutron was captured by ^{10}B to form α-particle according to reaction with a total energy of 2.78 MeV

$$n + B^{10} \rightarrow Li^{7} + \alpha + \gamma + 2.78\ \text{MeV}.$$

Most of the energy in this reaction (1.47 MeV) takes α-particle and spends it on the production of scintillation signal which is equivalent to a signal of an electron with an energy of 76 keV. The α-particle has negligible mean free path and therefore is registered at the place of its formation in the detector. Measuring the neutron signal gives us improvement of the rejection power between the electromagnetic and hadron-nuclear primary particles.

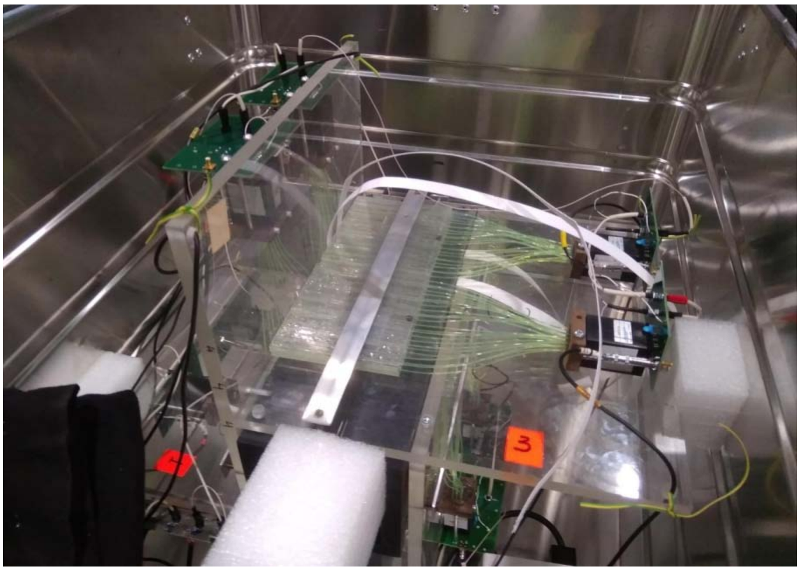

Figure 2. The borated scintillator planes OLVE-HERO inside of light-tight metal container

1.2 Results of OLVE-HERO beam test at SPS

Tests of the prototype were carried out on the test area at the SPS CERN. Fragmentation nuclei from the lead nucleus with an energy of 13 Gev/c and a rapidity in the test channel A/Z = 2.1 - 2.2 were used. The intensity of a beam of nuclei was ~5000 particles per spill. Amplitudes of signals from the BS plates, the calorimeter and CMS plates were recorded in a time window of 16 µs after the generation of the trigger. The trigger was produced by coincidence of signals from forward trigger detector T1 and backward trigger detector (calorimeter) T2 as shown in principial measurement scheme at Figure 3.

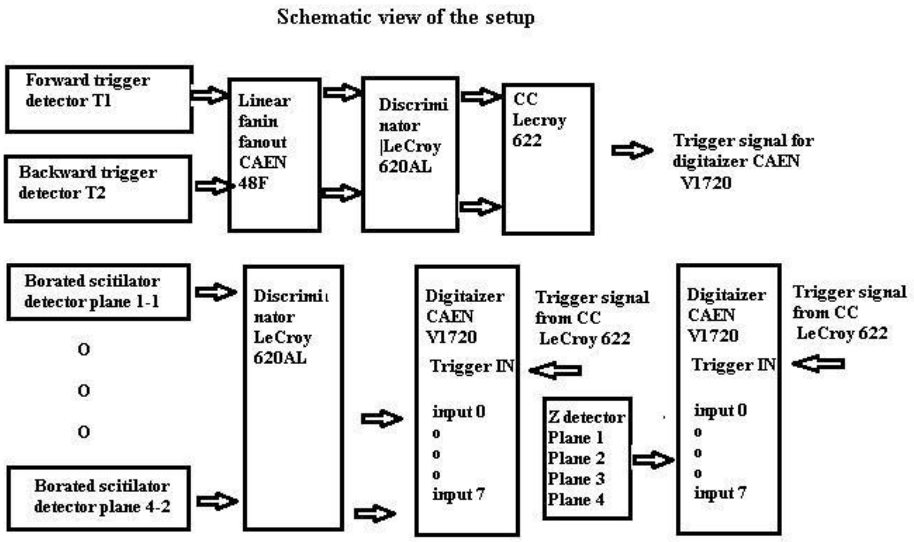

Figure 3. The measurement scheme

In order to check the operation of the CMS was for three CMS planes built a three-dimensional histogram. It is presented in Figure 4. The linear dependence of the CMS amplitudes shows the correct operation of the system.

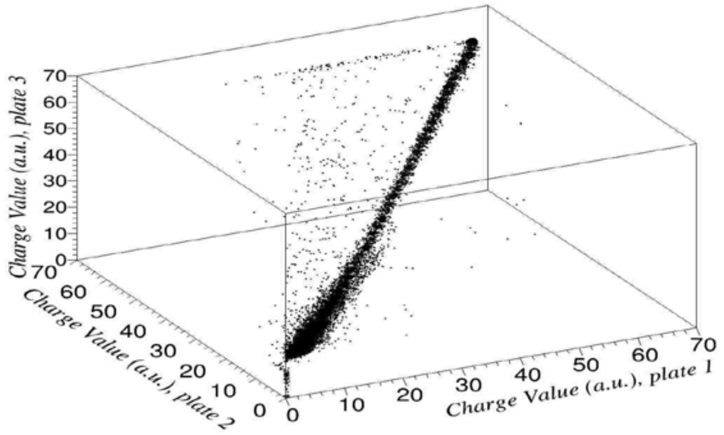

Figure 4. Amplitude correlation of charge measurement detectors

In Figure 5. is shown an example of the recorded data in the 16 µs time window. Beam particle interaction in the target generates a cascade of secondary particles which gives signals in all the detectors almost simultaneously with trigger signal. They all are shifted on 3.5 µs for visibility. Besides of coincided signals in the trigger time there are visible two delayed signals at the ~5.5 and ~8.5 µs. They are typical BS signals of thermal neutrons.

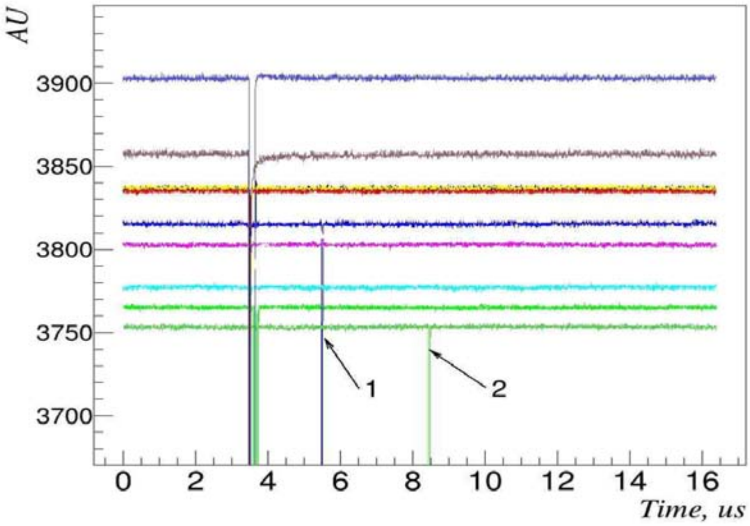

Figure 5. Example of time dependencies for the single event amplitudes with neutron peaks (1 and 2).

In Figure 6 is shown the time dependence of signals in lateral downstream BS detectors. The number of signals in the 16 µs window after the trigger time decreases and signals are interpreted as neutron signals.

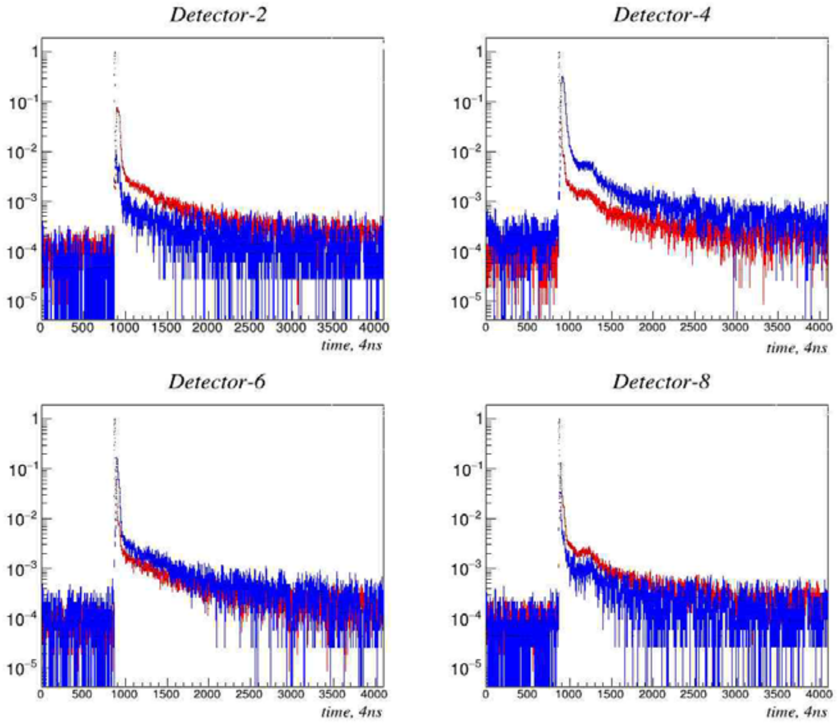

Figure 6. The time dependence of the neutron signals in the downstream BS detectors: blue - before the prototype shift, red - after the prototype shift.

An effect of the beam variation in the transverse plane was studied. The prototype was moved 30 mm to the bottom and additionally 40mm to the left of its initial position. In the Figure 6 is shown the time dependence of the BS signals before and after the prototype movement. There is clear evidance that an effect of the beam variation is observed. To understand this effect we need to check it with the Monte-Carlo simulation that is presently in progress.

1.3 Results of Monte-Carlo simulation

The Monte-Carlo simulation was accomplished for better understanding of obtained measurements. It was carried out using the framework of software packages FairRoot and Geant4. Figure 7a shows the time dependence of α-particles created in BS planes in 16 μs time interval. The time when the beam particle enters the prototype is zero. To check the effect of boron on the number of α-particles yield, Figure 7b shows the time dependence of signals in the BS planes without boron.

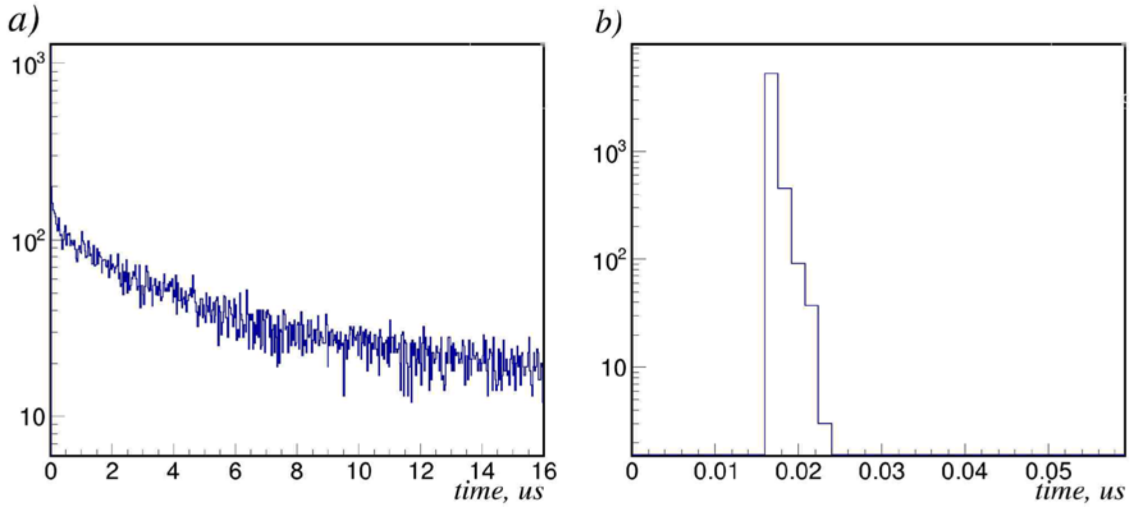

Figure 7. Monte Carlo simulation of the α-particles time creation in the prototype: a)with borated scintillator, b) without boron. Time shift in the right panel is due to distance between the beam entrance point and the scintillation detector.

The beam particle interaction generates evaporative and thermal neutrons in all planes. The equilibrium of the thermal neutron density to beam flux intensity during the beam pulse was established. But in real OLVE-HERO experiment we have to withstand the constant flux of 300000 neutrons. It will determine the value of a constant background signal in the future OLVE-HERO borated scintillator calorimeter. To study this effect in prototype like shown in the Figure 1 was by Monte-Carlo simulated distribution of the lifetimes of delayed and thermalized ~300000 neutrons with carbon nuclei as beam particles. The lifetimes of delayed neutron for the BS detector-1 are presented in the Figure 8. It gives an average lifetime T_n since neutron entered the prototype of the thermalized neutrons. T_n depends on the maximal energy E_n cuts: red $E_n<14$ MeV (T_n = 0,7 ± 0,003), blue $E_n<1$ MeV (T_n = 0,9± 0,003), green $E_n<0.1$ MeV (T_n = 1.4 ± 0,003), violet $E_n<0.01$ MeV (T_n = 1,8 ± 0,008) .

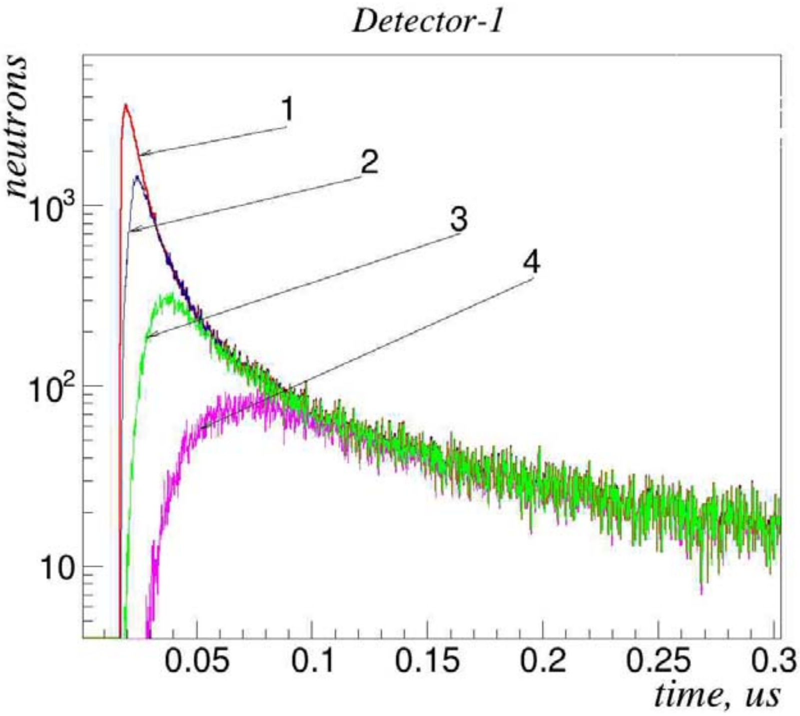

Figure 8. Monte-Carlo distribution of the lifetimes of delayed neutrons in the BS detector: Red (1) E_n<14 MeV, blue (2) E_n<1 MeV, green (3) E_n<0.1 MeV, violet (4) E_n<0.01 MeV

1.4 Conclusion

The results of the OLVE-HERO prototype calorimeter tests on lead ion beam at the SPS CERN at 2018 are presented. From the beam test results and Monte Carlo simulation one can conclude that the borated scintillator detectors give a possibility to increase the rejection power between the hadron CR component and the electromagnetic one. Using a borated scintillator in the prototype together with a polyethylene moderator gives a clear picture of the appearance of delayed signals from the neutron capture by ^{10}B nucleus in the range of 0 - 16 µs since the primary interaction of the beam particle. The results are in qualitative agreement with the Monte Carlo simulation.

The CR flux generates evaporative and thermal neutrons. After the equilibrium of CR flux intensity and thermal neutrons density will be established, that will determine the value of a constant background signal in the borated scintillator detectors. This background signal can “clog” the signal from the initial CR showers, therefore one has o be sure that such a detector will not give wrong results. To obtain the final answer, it is necessary to carry out additional tests on the beams and a special simulation of this effect taking into account the spectrum and composition of the CR, as well as the geometry of the detector. In order to optimize the design of the OLVE-HERO detector, the additional data analysis, Monte Carlo simulation and additional experiments are required in particular on the high energy electron beam.

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