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"HADRON-55" complex setup for study of hadron interactions within the central part of cosmic ray extensive air showers (EAS) cores

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Abstract: "HADRON-55" with scintillation detectors and ionization calorimeters is used for studies in high-energy gamma-astronomy and cosmic ray physics. The "HADRON-55" consists of two parts - the upper gamma block and the lower hadron block. The gamma block absorbs and detects the electron-photon components of cosmic rays, while hadrons are not absorbed when they pass through the gamma block and begins to form particles in the hadron block. Project's main idea is to select events where there is the interaction in gamma block and no interaction in hadron block. Analysis of experiments results on "HADRON-55" accounts for ∼ 6% of such events. The peripheral part of "HADRON-55" consists of 8 scintillation detectors placed in 2 circles with radii of 40 and 100 m. Over 4 years, more than 120,000 events with high energy of 10^{15} eV were detected.

Keywords: Calorimeter methods; Calorimeters; Particle detectors

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Contents

1 Introduction

It is often overlooked that elementary particle physics has come from cosmic ray physics. After the outstanding results of particle physics due to advances in accelerator technology, we again witnessed some interest in studying of ultrahigh-energy cosmic rays. The main research interest in Hadron-55 is directed at studying cosmic rays with energies above 10^{15} eV.

This year we have started a new cosmic ray experiment at the Tien Shan High Mountain Research Station (TSHMRS) located at an altitude of 3340 m above sea level 45 km far from Almaty city. There we have assembled a new HADRON-55 hybrid setup consisting of a two-storey coordinate scintillation-ionization calorimeter (CSIC) of 55 m^2 in area and a dense array of scintillation detectors which cover the calorimeter itself as well as the adjacent territory [1, 2].

Main advantages of the constructed HADRON-55 setup are a possibility to determine the energy of the primary radiation as well as its capability to measure the angular, lateral and longitudinal distribution of secondary particles in the atmosphere and in the lead absorber. It is also very important that the setup makes it possible to study different components of air showers by providing experimentalists with comprehensive information on the studied phenomena [3].

2 The "HADRON-55"

2.1 The HADRON-55 setup design

The HADRON-55 (we also call 'calorimeter') setup represents a two-tiered coordinate scintillation-ionization calorimeter (CSIC) of 55 m^2 in area and 1050 g/cm^2 deep (figure 1) surrounded by a dense array of scintillation detectors which will be extended in future outside the laboratory building and will cover an area of more than 2 km^2. The tiers are spaced vertically by 2.2 meters. The upper

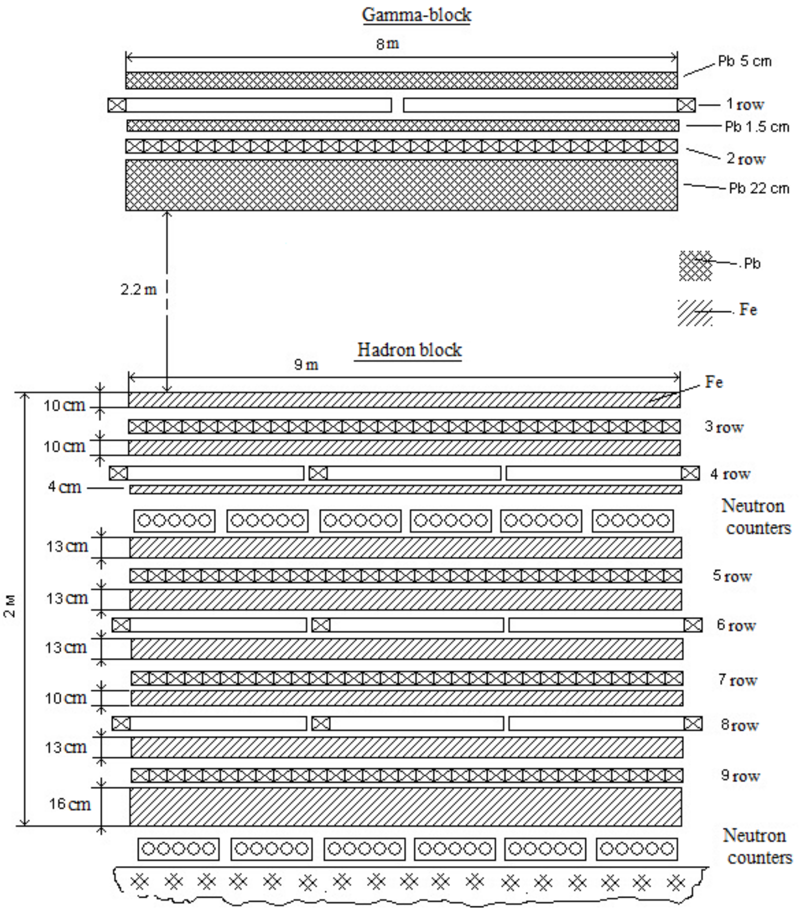

Figure 1. A two-tiered coordinate scintillation-ionization calorimeter of the HADRON-55 setup.

deck (called the Gamma-block) contains two rows of ionization chambers (IC) (100 IC in the first row, 138 in the second and filled with argon) under it, which are arranged in mutually perpendicular directions. Beneath them, there is a target lead block of 22 cm (250 g/cm^2) thick in which hadrons of cosmic radiation interact effectively with lead nuclei. The design of the upper tier installation makes it possible to determine the energy of electron-photon component and, in conjunction with the lower tier (Hadron-block) enables experimentalists to reconstruct the particle trajectories. There are also 24 scintillation detectors 0.25 m^2 each which are spread over an area of 324 m^2 at the level of the upper tier.

The lower tier consists of 6 rows (from 3 to 8 rows) of ionization chambers (144 IC in each row), which consists of iron absorber with gaps where IC, neutron and Geiger counters are placed [3]. The Geiger counter is used to detect the muon component of EAS, and the neutron counters are used to detect neutrons. Neutron counters filled with Argon and Helium-3. Series modules are assembled in 6–7 pieces. Total area 54 m^2. The deceleration of neutrons occurs due to a case made of wood. This unit (lower tier) is used to measure the energy of the charged cosmic ray component as well as to determine the particle trajectories. The specific feature of the HADRON-55 setup is that it represents a set of different detectors by allowing a much more detailed study of characteristics of cosmic ray particle interactions.

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According to [4] and our calculations [5] the error in determination of interaction energy in an ionization calorimeter of 1,000 g/cm^2 thick containing six levels of registration is about 10%. Therefore the calorimeter's design has 9 rows of detectors and the total thickness of the absorber is 1033 g/cm^2 that is sufficient for a correct determination of the primary particle energy E_0 with a reasonable accuracy.

It is envisaged that, in the nearest future, the HADRON-55 setup will work as a part of a new shower array which is now under construction at TSHMRS. This array represents a network of scintillation detectors located on an area of about two km^2. Thus, measurements of the primary particle energy E_0 and determination of their mass should be performed more reliably that makes it possible to solve the problems planned.

2.2 Ionization chambers used in the "Hadron-55"

The upper tier of the IC (i.e., G-block) consists of two rows of IC arranged in mutually perpendicular directions. The first row contains 100 ICs and the second one comprises 144 chambers of size $300 \times 11 \times 6\,\text{cm}^3$ each. The signal read-out of each IC is performed with in-house electronic recording channel developed and fabricated in TSHMRS. Figure 2 presents a schematic block diagram of a recording channel of ionization chamber consisting of 544UD1 chips of operational amplifiers and the SMP04 cell of analog memory. At the input of the amplifier, there are diodes D1 and D2, which limits the input voltage and partially compress the input range to a logarithmic scale. In the feedback circuit of the output cascade of amplifier at the 544UD2 chip, a diode is also installed which provides a quasi-logarithmic transfer characteristic of the amplifier. The amplifier of ionization chamber makes it possible to boost signals from 100 µV up to 100 V that means that it has a dynamic range (gain) of 10^6.

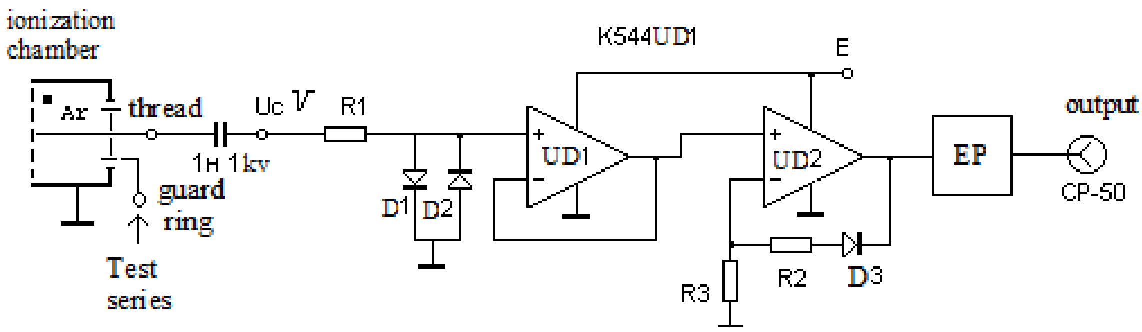

Figure 2. A schematic block diagram of the logarithmic amplifier of an IC recording channel.

Figure 3 shows the calibration characteristic of a logarithmic amplifier. The graph shows that for signals from 100 µV to 10 mV, the measurement error is less than 10%, and for signals from 10 mV to 100 V, the measurement error is less than 1%. We call such a graph the transfer function, where the vertical axis on the left shows ADC code, the error on the right and horizontal axis shows the voltage.

2.3 Scintillation detectors used in the IC

To detect electron EAS component, the HADRON-55 setup uses scintillation detectors fabricated on the basis of solid plastic scintillators which contain luminescent substances emitting light when

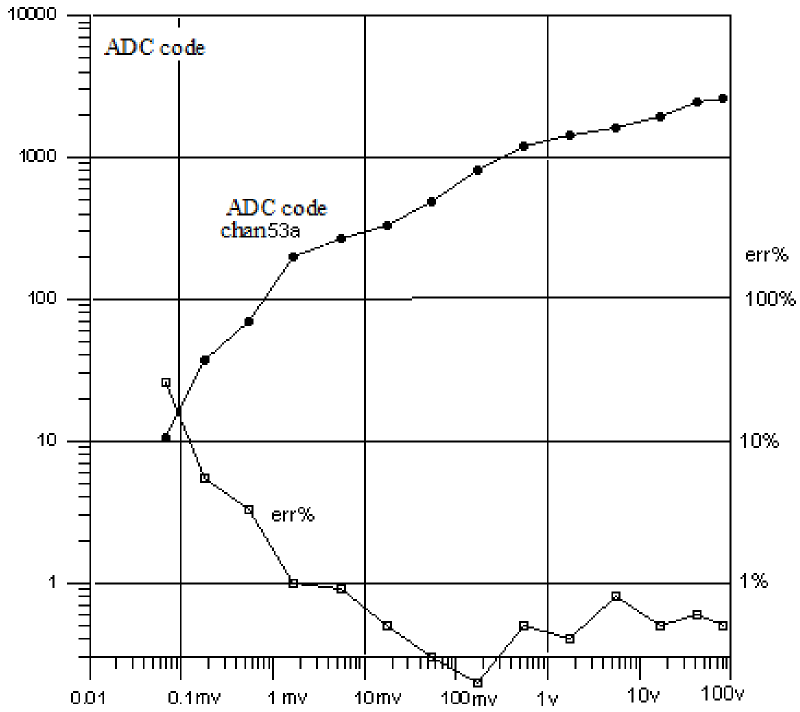

Figure 3. Transfer function of the amlifier of ionization chamber.

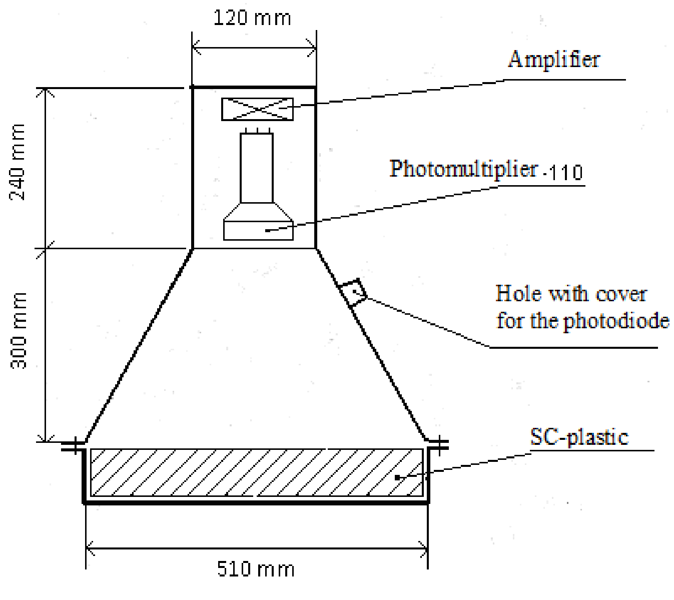

Figure 4. The design of the scintillation detector.

charged particles pass through them. The light pulses are recorded by a photomultiplier tube (PMT-110 in our case). Figure 4 shows the structure of the scintillation detector.

A light-tight casing of the scintillator is made of an aluminum sheet of 1 mm thick and is covered inside with white reflective paint. In the lower part of the casing, there is horizontally mounted plastic block of $50 \times 50\,\text{cm}^2$ in size and 5 cm thick. The upper part of the body has the shape of a pyramid on top of which a photomultiplier is mounted together with a voltage divider for dynodes and a PMT signal amplifier. Currently 24 scintillation detectors are installed.

2.4 Neutron detectors of the IC

The method of energy measuring based on the detection of evaporated neutrons from the nuclei splitting produced by cascade particles was proposed about 30 years ago [6] and is used in analyzing the data of the world network of neutron monitors [7]. However, neutron calorimeters have not yet been widely used. Our project by using a two-tiered IC combines two different methods of particle energy measuring, i.e., the ionization calorimeter method and that of the neutron one. The efficiency of the combined calorimeter is substantially higher as compared with ionization and neutron calorimeters individually [8]. Indeed, in addition to determining the energy of two independent methods, IC is able to separate gamma rays, electrons and hadrons in the mixed flux of particles due to the relative neutron yield in electromagnetic cascades as compared with nuclear ones, which is not more than 5–10% [9]. When neutron moderation to thermal energies is used for neutron detection, the design of the IC is practically the same as of common calorimeters. In this case, the signals from neutrons will be delayed regarding to the ionization signal to tens or hundreds of microseconds because of thermalization and diffusion processes in the material of the inhibitor. Therefore, detection of ionization and neutron signals can be conducted by the same detectors, such as gas proportional neutron counters, with some shearing in time.

The detection technique of the neutrons presently used at the Tien Shan mountain station is based on the $30 \times 1000\,\text{mm}^2$ gas discharge counters filled with a mixture of natural argon and enriched ^{3}He, under partial pressure of 2 atm, diameter of the anode wire is 3 mm. The neutron detection is possible there due to nuclear reaction n(3He,3H)p.

The IC has two rows of neutron detectors [10]. The first one is between the fourth and fifth registration rows, and the second one is just after the 9th row (see figure 1). This arrangement of neutron detectors allows us to determine independently the primary particle energy [11], number of neutrons and their lateral distribution function in the calorimeter.

2.5 The trigger and the readout systems

The HADRON 55 setup trigger system assumes selection of events by several EAS parameters: total ionization, density of charged component, position of the EAS axis (hitting parameters), etc. The event registration is done by recording detector signals in a computer memory according to a special control (trigger) signal which is generated in a special electronic unit of the setup. It is supposed that the triggers system of the setup will have four different modes. However, nowadays we use only the 1st mode of trigger system operation based on the circuit processing the sum of ionization in two detection levels (rows) of the G-block. The readout system (128 read-out channels) includes a computer and a software package of management, control and processing. The program manages the readout process through the computer's LPT parallel port, then through the CAMAC data controller which transfers data to the computer memory from the ADC modules installed in the CAMAC crate. The database is formed with events accumulation in the computer memory.

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3 Results and conclusions

3.1 Detector performance

In the first and second rows of the gamma block, ionization chambers are located in mutually perpendicular directions. This allows to determine the direction and energy of showers passing through this layer, which forms the first level of ionization calorimeter. The third and fourth, fifth and sixth rows of the ionization calorimeter, forming the second and third levels, are considered in a similar way. The three levels of ionization calorimeter are presented in figure 5. The X and Y axes show the location of ionization chambers. On the Z axis, the amount of ionization during the passage of charged particles is shown. For this event, the zenith angle is 7°, azimuth angle is 205°. The energy of the primary particle is $3 \cdot 10^{15}$ eV.

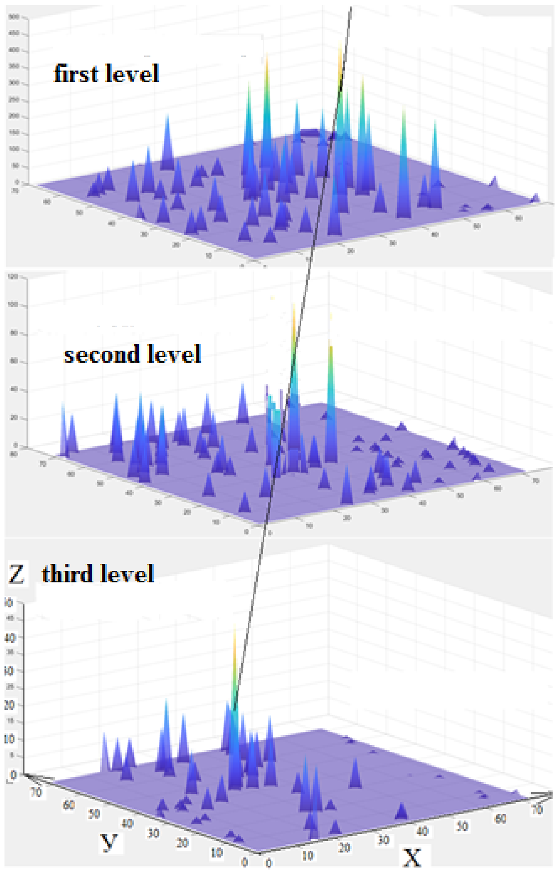

Figure 5. Illustration of the position of the axes of EAS event No. 9 in the plane of the "carpet" of the ionization calorimeter.

In order to verify the correct operation of the entire electronics of calorimeter, the adequacy of programs and methods for calculating the energy of primary particles, we calibrated the setup by determining the flux of particles of cosmic rays with an energy of $E_0 \geq 3 \cdot 10^{12}$eV. It is known that the flux of cosmic particles at a given height is a fairly stable and well-studied quantity. Therefore, a comparison of the experimentally measured flux values on a new installation with results obtained

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on already well-tested plants that have worked stably for a long period allows us to estimate the accuracy of measurements on our plant. It was logical to compare our data with work results of the ionization calorimeter of the Tien-Shan plant of P.N. Lebedev Physical Institute of the Russian Academy of Sciences, located on the same site with our calorimeter. According to their data of [12], the total particle flux at an altitude of 3340 m is $I(\geq 1\,\text{TeV}) = 0.8\,\text{ptc/m}^2\,\text{sr}\cdot\text{h}$. The particle flux obtained in our experiment is equal to $I(\geq 3\,\text{TeV}) = 0.15 \pm 0.01\,\text{ptc/m}^2\,\text{sr}\cdot\text{h}$. To compare flows, it is necessary to bring them to the same threshold energy. If we bring our value to the energy of 1 TeV, then we get $(\geq 3\,\text{TeV}) = (0.82 \pm 0.04)\,\text{ptc/m}^2\,\text{sr}\cdot\text{h}$, which well coincides with the data of [13]. Thus, all the systems of the created installation HADRON-55 work correctly and in a steady mode. This year about six thousand events were recorded with energies greater than $2\cdot 10^{15}$ eV. The interactions when the share of primary energy is transferred only to the neutral component is 6%.

3.2 Conclusion

Using the methodology for processing data obtained in cosmic rays studies on the HADRON-55 installation searches for similar structures in the data obtained at high-energy accelerators, that is, in the future we can compare this data with the data obtained at particle accelerators.

In addition, the data obtained using HADRON-55 will be used in other experiments conducted at TSHHSS [14].

Acknowledgments

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