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# PROJECT FOR MODIFYING THE SETUP FOR ADRON-55 TO IMPROVE ITS BACKGROUND CHARACTERISTICS AND A REVIEW OF UNSOLVED PROBLEMS IN STUDIES OF EXTENSIVE AIR SHOWERS

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*The article presents an overview of modern problems in studies of Extensive Air Showers and works devoted to their investigation. It is demonstrated that over the past decade convincing evidence of the presence of a neutron component has been demonstrated. When designing experimental facilities aimed at studying the nature of cosmic rays, this must be taken into account, since fast neutrons that arise outside the working volume can adversely affect the interpretation of the obtained data. In particular, if one tries to reveal the nature of penetrating component this effect is at most importance. Studies of biological shielding for the high flux research reactor PIK reactor at the Kurchatov Institute have shown that effective shielding from such neutrons can be provided by polyethylene in combination with borated rubber. At the same time, the use of boron-containing polyethylene does not lead to a significant improvement in protection, however, it significantly increases its cost. Based on foregoing, a modification of the hadron calorimeter protection is proposed to improve its protection it from the influence of the fast neutrons.*

**Keywords:** cosmic rays, extensive air showers, high-energy particles, ionization calorimeter, penetrating component

## Introduction

The study of the nature of cosmic rays has a long history, and it can be said that its origins are already almost one century away from our time. As early as the beginning of the twentieth century, Victor Hess discovered [1] that natural radioactivity on the Earth's surface is only partially due to radioactive decays of elements in the soil and surrounding objects. In the course of his experiments with the rise of ionizing radiation detectors on balloons, he showed that starting from altitudes of more than 1 km, the radiation background began to increase. Moreover, this background did not depend on the time of day and did not decrease even during a solar eclipse, and, as Hess correctly suggested, the source of this ionizing radiation was obviously outside the Earth's atmosphere and was of cosmic origin.

Nowadays, cosmic rays are detected using many different facilities from Cherenkov telescopes such as H.E.S.S., MAGIC, VERITAS, neutrino detectors of the “Kover-2” type of the Baksan Neutrino Observatory, and to detectors of high-energy charged particles, incl. hadrons. Despite the fact that studies of cosmic rays have been going on for more than a century, in this area there are still such unsolved problems as the nature of the appearance of particles with energies exceeding $10^{19\div20}$ eV [2], the origin of a break in the energy spectrum [3], and the presence of extensive air showers (EASs) of the penetrating component [5, 6].

To approach the solution of the problems listed above, for example, to clarify the nature of the EASs penetrating component, it is necessary to have data with high fidelity. All known systematic effects should be excluded or minimized, preferably before the analysis. Therefore, section 3 contains the result of the investigation at the Kurchatov Institute concerning the biological shielding at the PIK nuclear reactor. It also proposes modification project for hadron calorimeter in order to reduce the influence of thermal neutrons which can pose some problems to the data analysis if not excluded.

## 1. Review of unsolved problems and attempts of their modern interpretations

There are three problems that are marked as unsolved for today: the maximum energy of cosmic radiation particles, the energy spectral composition (namely, a sharper cutoff at high energies than the theory predicts), and the presence of a penetrating component. Let's start by looking at the first of them.

It would seem, as we know, that there are many places in the Universe where nature acts like a natural laboratory, for example, the magnetic field of magnetars reaches $10^{10\div11}$ T [7, 8] and charged particles in such fields can be accelerated to colossal energies. However, since the Universe is isotropically filled with cosmic microwave background at a temperature of ~3 K, then upon reaching a certain energy threshold, charged particles will interact, which will lead to their deceleration and, consequently, to energy loss. This limit was first calculated by G. T. Zatsepin, V. A. Kuzmin [9] and, independently, by Greisen [10]. The characteristic time of interaction of a proton with a kinetic energy of $10^{20}$ eV with cosmic microwave background radiation is estimated at $10^7$ years, which means that when moving at a near-light speed, the maximum distance that these protons would be able to overcome is 100 million light years or about 30 Megaparsecs, but the main problem is that we do not know the direct sources of such rays. Attempts to explain this effect are still ongoing [11,12], including with the use of recent observations showing both anisotropy in the distribution of ultra-high-energy cosmic rays and suggesting that perhaps the highest-energy component may not consist of protons, but of heavy nuclei for which the Greisen-Zatsepin-Kuzmin limit has a different meaning.

The second unsolved problem is the presence of a break in the EAS energy spectrum, which was discovered as early as the middle of the last century [3]. At present, there is no well-established hypothesis [4] that somehow explains its origin, since there are still discrepancies in the results of experiments, for example, in the dissertation [13] by O. B. Shchegolev on pages 13-14, it is shown that for an experiment with a calorimeter KASCADE the so-called "knee" is not observed. And in an article by researchers from the FIAN, it is analytically shown that if a “kink” is observed, then it must have precisely an astrophysical nature [14].

Finally, the presence of the EAS penetrating component also does not have a strong explanation today, and there are suggestions that increased ionization in the deep layers of the calorimeter can be caused both by high cross sections for the production of exotic particles containing heavier generations of quarks, such as charm and strange) [5, 6], and partially explained by the presence of high-energy neutrons in the hadronic component [16], which also made it possible to explain the presence of delayed signals in external detectors.

The point is that if the energy of the primary particle is sufficiently high, and the axis of the EAS (extensive atmospheric showers) passes near the detectors, then a large number of evaporation neutrons are produced, which require some time for thermalization. The penetrating power of fast neutrons through traditional lead shielding is quite high, and they led to additional delayed detector responses.

## 2. Scheme of the Hadron-55 facility and evaluation of the effect of fast neutrons produced in EASs.

The Hadron-55 installation consists of several key components:

1. Two-tier coordinate ionization calorimeter
2. Central shower installation of 30 scintillation detectors
3. Peripheral detectors at distances of 40 and 100 meters from the ionization calorimeter.

The ionization calorimeter is designed to detect charged particles from extensive atmospheric showers and makes it possible to determine the energy of the primary particle. The central shower facility makes it possible to determine the moment of arrival of the EAS front and generates a trigger signal to start recording all subsequent events in the calorimeter. Finally, peripheral detectors also register the EAS arrival moments and, from the time difference, make it possible to reconstruct the zenith angle, and, consequently, the direction of arrival of the primary particle. On Fig. 1 shows the design of an ionization calorimeter. More detailed information about the location of all components of the installation and the principles of operation can be found in the relevant works [16, 17].

It can be seen that a significant part of the calorimeter is occupied by sheets of lead and iron, which usually work well as a shield against ionizing radiation, if we are talking about charged particles or gamma rays. However, it is known that for neutrons, especially for fast neutrons, lead is an extremely poor shield for two reasons. First, it is known that, in the general case, the cross section for the interaction of neutrons with matter decreases with increasing energy. For example, if we turn to the ENDF (Evaluated Nuclear Data File) database and build graphs for the total cross section for the interaction of fast neutrons with matter, then we will see the following picture presented in Fig. 2: namely, the interaction cross section for neutrons with energies on the order of tens of MeV are at the level of units, with a maximum of tens of barns. At the same time, their kinetic energy is almost millions of times greater than the thermal energy of the substance with which they interact. Though. we can assume that the neutron hits the target at rest.

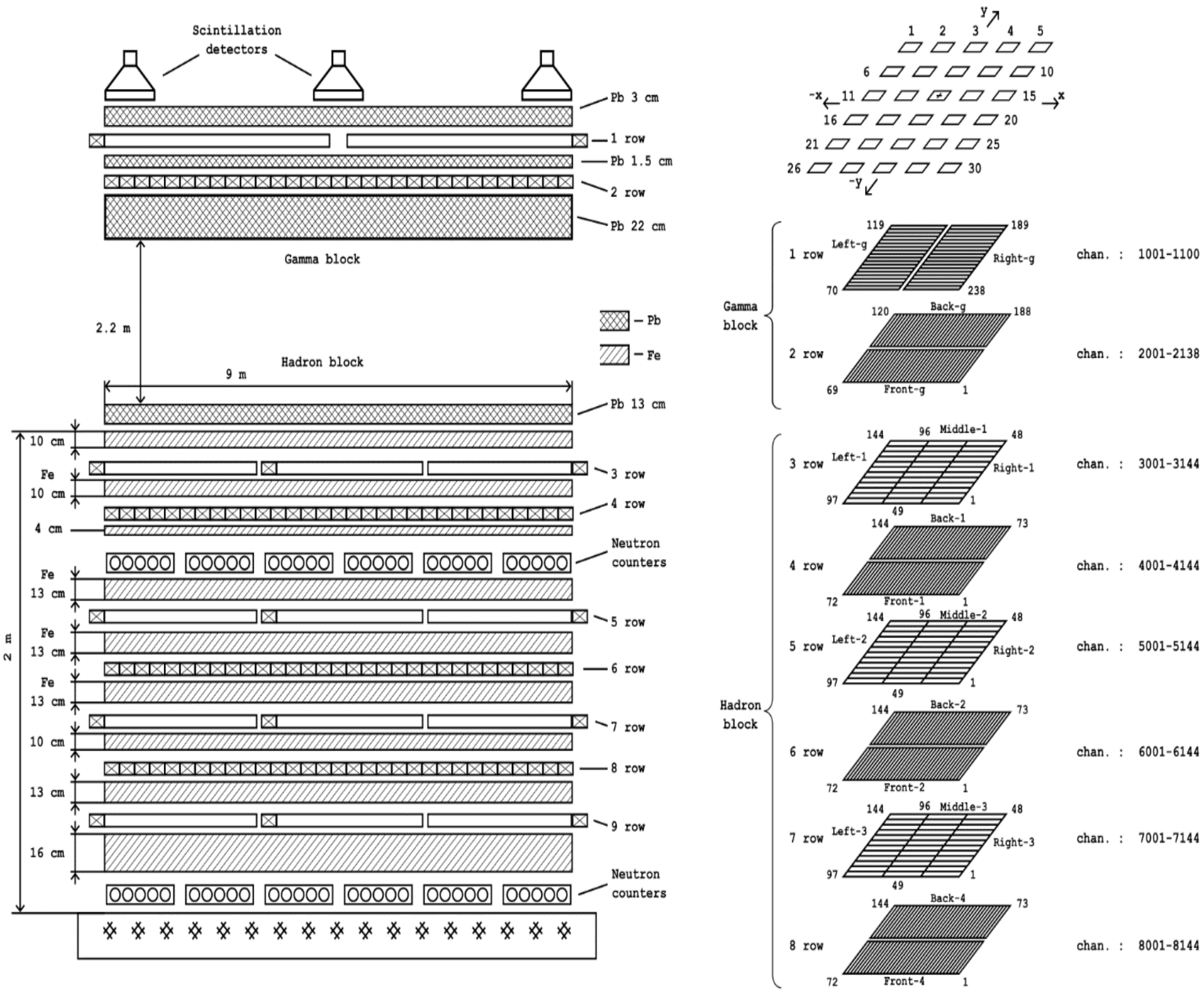


**Fig.1.** Scheme of the Hadron-55 ionization calorimeter. Image on the left - vertical section of the calorimeter, on the right - location of scintillation detectors and rows of ionization chambers.

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If we neglect change in velocity in the act of one collision of a neutron with an atom, which is performed with good accuracy for heavy atoms such as lead or iron, then if the neutron's the velocity was equal to $v$, and during a unit time of flight it experienced m collisions, then, obviously, the free path λ will be is equal to:

$$\lambda = \upsilon/m, \tag{1}$$

where υ - the neutron's velocity in collision with an atom;

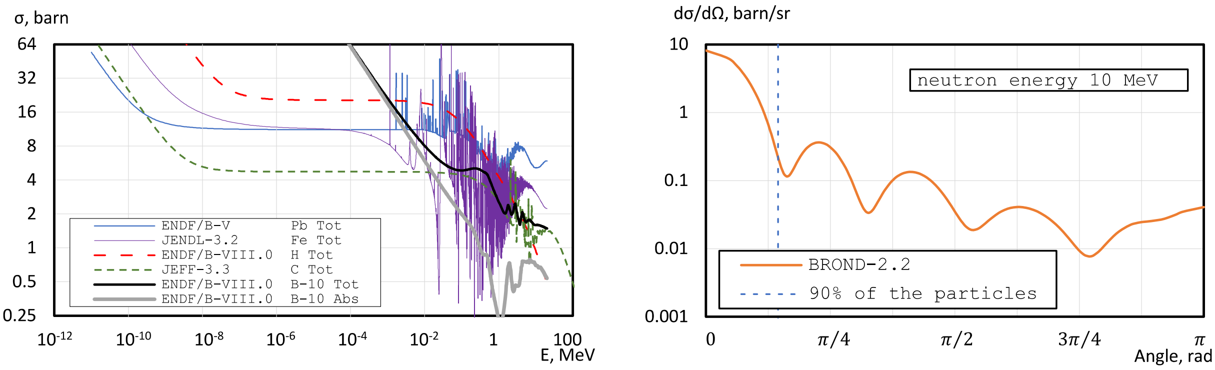
m – number of collision per unit time.

In a unit time interval, a neutron will travel a path υ and "sweep" a volume equal to συ in its motion, and multiplying by the concentration of atoms per unit volume *n*, we get the number of collisions per unit time *m*:

$$m = \sigma v n \tag{2}$$

And the mean free path λ is then equal to:

$$\lambda = \frac{1}{\sigma n} \tag{3}$$




a) b)

**Fig.2.** a) Dependence of the total interaction cross section for neutrons of different energies; b) differential Cross section for the interaction of neutrons with an energy of 10 MeV in collisions with lead nuclei

The score obtained by order of magnitude in this way is shown in Table 1. It can be seen that the path length of ~10 MeV neutrons in lead is on the order of several centimeters. But it must also be taken into account that this is only the average path length, and most of the neutrons (more than 90%) on average deviate from the initial direction by an angle of less than 26 degrees, which is shown in Fig. 2b.

**Table 1.**

| Substance | ρ, g/cm$^3$ | a.m.u | n, ($10^{22}$) | σ(10MeV) | λ, cm |
|---|---|---|---|---|---|
| Pb | 11.3 | 207.2 | 3.28 | 5.2 | 6 |
| Fe | 7.8 | 55.45 | 8.52 | 10.3 | 1 |
| $CH_2$ | 1.2 | 14 | 5.14 | 1.01 | 19 |
| $H_2O$ | 1 | 18 | 3.33 | 2.34 | 13 |

The solid curve is the dependence of the differential cross section on the angle. Even on the logarithmic plot, ninety percent of the area under the curve is contained within the 0.26° angle interval. That is, fast neutrons represent a significant difficulty in measurements. However, this is only the first of the problems. The second is that lead works extremely poorly as a neutron moderator. Indeed, in a frontal elastic collision of two bodies with equal mass, according to the law of conservation of momentum, the incident body must stop, and the body at rest must fully acquire its momentum and continue moving.

In the case when the masses of the bodies differ by a factor of 3 or more, and the collisions occur at arbitrary angles, there is an approximation ξ that makes it possible to estimate the logarithm of the ratio of the initial energy $E_0$ to the energy after the collision E [18]:

$$\xi = \ln\frac{E_0}{E} \cong \frac{2}{A+2/3}$$
(4)

That is, for lead (A=207), ξ~0.01, which means that about 207/0.01~20·$10^3$ collisions are needed before thermalization. Also, using the simplified formula [18] for the thermalization time $\tau_0$ for lead, you can get:

$$\tau_0 = \frac{2\lambda}{\xi v_\tau} \cong 5\ ms$$
(5)

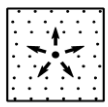
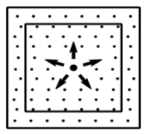
The situation can also be complicated by the fact that fast neutrons produced outside the calorimeter can be partially but more effectively slowed down by other materials containing lighter nuclides and give an additional excess background, which can complicate the interpretation of obtained data.

### 3. Proposal for modification of the protection of the ionization calorimeter

As described below, the neutron background can present a significant problem in measuring the energy of EAS particles, especially if we are interested in a time interval of ~1 ms. Articles devoted to the study of the EAS neutron component [19] also provide data indicating the existence of events where an anomalously high neutron multiplicity (M>1000) is observed. Thus, if the setup is not aimed at studying EAS by detecting the neutron component, the suppression of the background associated with it is highly desirable.

In 2020, in Nuclear Research Center of Kurchatov Institute research on the effectiveness of biological protection in the PIK high flux reactor hall from the neutron component has conducted, the results of which can be applied in this case as well.

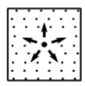
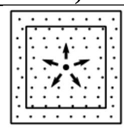
**Table 2**. Comparison of the most effective types of protection against fast and thermal neutrons

| Detector Configuration | | Configuration source | Fast neutrons | Thermal neutrons | Thermal neutrons |
|---|---|---|---|---|---|
| | | | Source without protection | Source in polyethylene (5 cm). | Source in polyethylene (10 cm). |
| | | |  |  |  |
| 1 | Polyethylene 5 cm. |  | $257.3 \pm 0.16$ (1) | $269.94 \pm 0.16$ (1) | $183.8 \pm 0.2$ (1) |
| 2 | Borated polyethylene 5%, 5 cm. |  | $19.85 \pm 0.09$ (12.96) | $18.3 \pm 0.08$ (14.75) | $11.24 \pm 0.03$ (16.35) |
| 3 | Borated rubber + Polyethylene (5 cm) |  | $255.29 \pm 0.16$ (1.01) | $244.03 \pm 0.16$ (1.11) | $162 \pm 0.34$ (1.13) |
| 4 | Polyethylene (5 cm) + Boron rubber |  | $4.61 \pm 0.03$ protection factor (55.81) | $4.19 \pm 0.02$ protection factor (64.42) | $2.36 \pm 0.03$ protection factor (77.88) |

A plutonium-beryllium source with a characteristic neutron energy of ~10 MeV was used as a source of fast neutrons. In order to convert fast neutrons into thermal neutrons, a layer of polyethylene protection with a thickness of 5 and 10 cm was used. A scintillation detector based on a NaI crystal acted as a thermal neutron detector. Various materials have been used as protection, such as polyethylene, boron polyethylene with 5% or 8% boron content, and boron rubber with 20% boron content. The results of the most significant measurements are shown in Tables 2 and 3. The number without brackets means the count rate of the detector per second, and the protection factor is indicated in brackets. With an increase in the thickness of the source protection, the fraction of thermal neutrons increases, therefore, the protection factor against thermal neutrons increases.

To protect yourself from fast neutrons in the experiment, you must first thermalize them, for which polyethylene is used. A layer of 5 - 10 cm of polyethylene works quite effectively. It can be seen that borated rubber itself, despite the large absorption cross section of boron atoms, is unable to provide good protection not only from fast, but also from thermal neutrons.

**Table 3** Evaluation of the effectiveness of borated rubber as a shield against fast neutrons

| Detector Configuration | | Configuration source | Fast neutrons | Thermal neutrons | Thermal neutrons |
|---|---|---|---|---|---|
| | | | Source without protection | Source in polyethylene (5 cm). | Source in polyethylene (10 cm). |
| | | |  |  |  |
| 1 | Without protection |  | $22.15 \pm 0.05$ (1) | $83.52 \pm 0.13$ (1) | $107.7 \pm 0.2$ (1) |
| 2 | Borated rubber |  | $1.81 \pm 0.03$ protection factor (12.24) | $3.81 \pm 0.02$ protection factor (21.92) | $2.73 \pm 0.03$ protection factor (39.45) |

However, when it is used together with ordinary polyethylene, it is possible to obtain good suppression of the neutron background. Moreover, the rubber should act precisely as an inner layer, and not an outer one.

## Conclusion

The study of EAS is an intensively developing branch of physics. In the light of new research, it becomes obvious that the hadronic component also includes a neutron component. Thus, data analysis becomes incomplete, so it must be considered when designing experimental setups.

Based on the foregoing, it would be highly desirable to improve the design of the hadron calorimeter by surrounding it with a neutron shield consisting of a layer of borated rubber and polyethylene, at least along the perimeter, so that neutrons produced in the immediate vicinity of the setup would not affect the interpretation of the data obtained. It is also possible to equip the entire complex with additional neutron detectors, whose design is described, for example, in [21].

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