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ELEMENTARY PARTICLES AND FIELDS
Experiment

Muography of Large Natural and Industrial Objects

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1. INTRODUCTION

One of the modern approaches to solving research and practical problems by studying internal structure of large natural and industrial objects on the base of muon radiography (muography) is presented. A large number of problematic geologically active zones on the Earth surface, the state of which poses a threat to the infrastructure located in them, require constant monitoring. For this purpose, as well as for the study of cultural heritage objects, in particular, when studying their hidden elements or damage, the muography method [1] can be used. The method, which is at testing and initial implementation phase in Russia, enables to solve these problems in an affordable and safe non-invasive way and provides for a three-dimensional image of the internal structure of the objects under study without damaging or destroying them. The method is based on analysis of the cosmic muon flux absorption during their passage through the substance of the object under study.

Muons are generated in decays of kaons and pions which are the products of nuclear interactions of primary cosmic rays with the atmospheric nuclei. Muon is an unstable particle, but due to the relativistic time dilation effect, cosmic-origin muons with energies up to hundreds of TeV travel considerable distances before decaying. The high penetrating power of these particles is conditioned by their non-participation in nuclear interactions. As a result, muons make up the main component of cosmic radiation at sea level (up to 80% of the observed particles [2]). Intensity of their vertical flux at the sea level is quite high (about one particle per 1 cm^2 per minute for energies $E\mu > 1$ GeV), and at incidence angle from 60° to 80° to the normal, the intensity of the muon component decreases by only 4 times, while under the same conditions, the nuclear component of cosmic radiation decreases by about 1000 times [3]. As a result, a notable part of the muon flux not only overpasses the atmosphere to ground level, but penetrates into the rocky soil to a depth of 2 km (see, for example, [4]).

Muons have a non-zero charge and participate in electromagnetic interactions, losing their energy in the processes of medium atoms' ionization, bremsstrahlung, and electron–positron pair formation. As a consequence, the muon flux gradually weakens with the depth of the substance, passage through the substance with a larger charge number leads to a greater weakening, since the path of a charged particle is inversely proportional to the medium density. These properties of muons make them a unique agent for probing large natural and artificial objects on and below the earth surface. Muography is based on the difference in the muon flux attenuation while passing through areas with different matter densities. By the differences in the muon flux attenuation degree in nearby solid angles, one can judge the inhomogeneities within the object in this direction (caves, conglomerates, etc.).

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2. MUOGRAPHY EXPERIMENTS WITH EMULSION DETECTORS

Muons that have a path larger than their trajectory in the object reach the observation level and can be recorded in detectors located on the side and below the object, with the size of the detector several orders of magnitude smaller than the size of the object itself. In muography experiment, the values of the azimuthal φ and zenith θ angles of the particle trajectories in a cylindrical coordinate system, where the Z axis is perpendicular to the detector plane, are determined. Analysis of the obtained data is aimed at finding anomalies in the angular distribution of the registered particles and is based on comparing the measured angular distribution of particles passing through the object in a certain direction with the distribution modeled in the absence of density anomalies. Modeling of muon flux passing through an object and comparing the simulation results with experimental data makes it possible to reconstruct the particularities of the internal structure of the object.

Muography is applied as a promising addition to geophysical methods [5], an analysis tool of seismic and karst processes [6], mineral exploration [7], radiation monitoring of nuclear power plants [8] and for non-invasive testing of industrial facilities (blast furnaces, bridge supports, etc.) [9, 10]. The method enables to explore natural ground caves and large cavities of artificial origin [11, 12].

In muography experiments, electronic equipment on scintillators is widely used (see [5–12]). However, the highest resolution (about 15 m for an object length of 1 km) can be provided by track detectors assembled from two-sided layers of nuclear emulsion [13]. Nuclear emulsion is a photographic material of high sensitivity capable of registering relativistic charged particles in the accumulation mode. The advantages of emulsion detectors, in addition to high resolution, are the ability to expose without personal presence of experimenter and work in difficult conditions, up to extreme, small (compared to electronic installations) dimensions and simplicity of design, independence from energy sources, etc. The most informative approach involves the use of two and more detectors registering angular distributions of muons in a certain direction from several observation points [14]. This approach enables to reconstruct the three-dimensional picture of the studied anomaly.

One of the most recent and well-known experiments on the muography method on base of nuclear emulsions, that gave the resonant result, was the study of Khufu's Pyramid (Giza, Egypt) within the framework of the international project ScanPyramids. The nuclear-emulsion detectors placed in the Grand Gallery and the Queen's chamber detected a previously unknown cavity in the pyramid body with a length of at least 30 m with significance higher than 12σ [15]. The result, which became a breakthrough in archaeology, was confirmed with scintillation hodoscopes and gas detectors.

Advantages of emulsion detectors are obvious when studying hard-to-reach objects or objects dangerous for human presentation. Perspectivity of nuclear emulsions in studies of this kind was demonstrated in experiments on the state of nuclear reactor monitoring after the Great East Japan Earthquake and Tsunami in 2011. Muography was proposed to determine the presence of nuclear fuel in the damaged unit of the Fukushima Daiichi nuclear power plant reactor [16]. Based on the data of the emulsion detectors, a comparison of its internal density with the density in the intact unit showed the absence of nuclear fuel in the damaged reactor unit. This result was also confirmed by scintillation detectors data [17].

Nuclear emulsion detectors were successfully used in an experiment on probing the Stromboli volcano (Italy) [18]. Muons were recorded for five months with a 0.96-m^2 detector. The result obtained enabled to identify a significant low-density zone at the summit of the volcano with a density contrast of 30–40% with respect to the bedrock.

In recent years, active development of muography with nuclear emulsion detectors started in Russia in connection with the revival of the nuclear emulsion production on the Russian company "Slavich". In 2012–2014, Lebedev Physical Institute (LPI) and MSU Skobeltsyn Institute of Nuclear Physics (SINP MSU) conducted a series of test muography experiments using emulsion track detectors. The first examined object was a steel column of 23 tons, considered as a massive absorber of atmospheric muons, which created a "shadow" in their flux. Emulsion layers were tightly packed in stacks of 10×12 cm^2 and rigidly fixed in frames of aluminum plates. The exposure continued for 49 days.

The experimental data were processed on the PAVICOM (LPI) and VISKAN-500 (SINP MSU) automated measuring complexes equipped with optical tables with high accuracy of moving and charge-coupled devices for optical images recording and digitizing. The hardware installed provided high-speed scanning and processing of the images obtained in the emulsion in real time. The result of each emulsion plate scanning is a data array with angular parameters of the identified particle tracks. The angular distributions obtained in this experiment demonstrated changes in the muon fluxes arriving at the detector in the selected range of angles, depending on the absorber thickness along the path, in accordance with the predictions of model calculations [19].

The second experiment with the exposure of 135 days was held at the Research Institute of the Tire

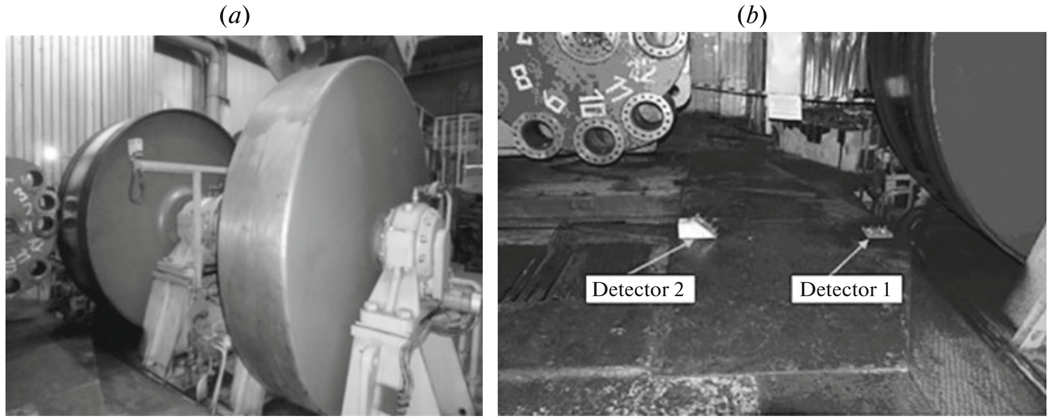

Fig. 1. (a) The test bench with massive parts (3 m in diameter each) for muography testing; (b) arrangement of the detectors on the test bench.

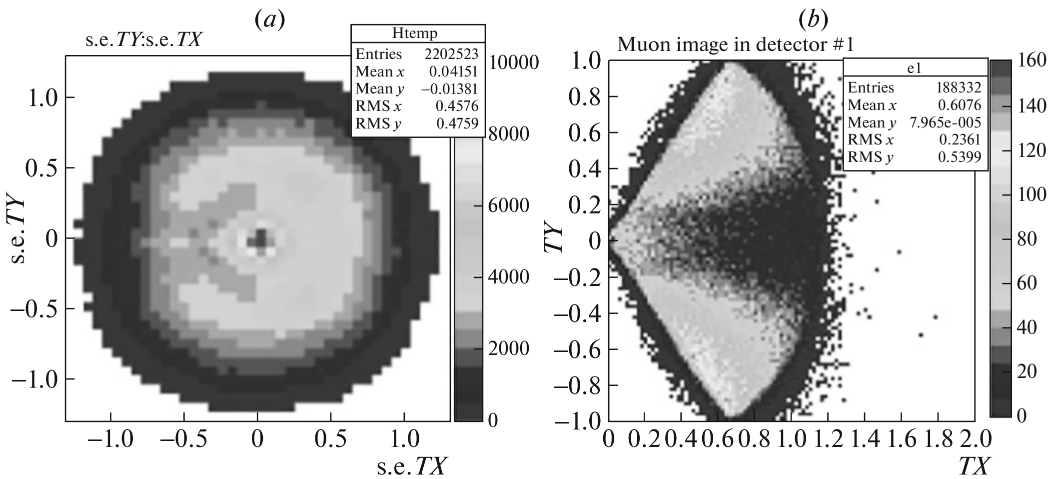

Fig. 2. Angular distributions of muons in detector 1 after passing the substance of the test bench: (a) experimental distributions obtained in the nuclear emulsion; (b) results of simulation.

Industry (Moscow). A couple of chassis dynamometer discs and an inertial element of the test bench, of 40-ton weight in total, were the observation objects (Fig. 1). The assembly scheme of the emulsion detectors was similar to the previous experiment, but the number of emulsion layers in the packages differed.

Figure 2 presents a comparison of the angular distributions of the registered muons in one of detectors (Fig. 2a) with the GEANT4 simulation results (Fig. 2b). "Shadow" from the running drum of the test bench is clearly visible on the both distributions, i.e. the experimental data obtained are in good agreement with modeling.

The data in Fig. 2 are presented in variables tx and ty, which are tangents of the track slope angles in the projections on (xz, yz) plane and are related to the traditional angular variables as

$$tx = \frac{dx}{dz} = \tan\theta\cos\varphi,$$

$$ty = \frac{dy}{dz} = \tan\theta\sin\varphi.$$

One more experiment on muography method was performed at a depth of 30 m in a mine located on the territory of the Geophysical Service of the Russian Academy of Sciences (Obninsk) [20, 21]. The detectors were placed at two observation levels (Fig. 3), in a mine underground and on the surface, to register the difference in muon fluxes. In addition, it was supposed to "see" the nearby elevator shaft with a diameter of 3.45 m. According to the measurements, muon fluxes at the surface and at a depth of 30 m differ by 50 times. Figure 3a shows the experiment scheme in the vertical plane, indicating position of the detectors and elevator shaft, and Fig. 3b presents the result of the obtained data processing. On the obtained experimental distribution, the frame highlights a singularity corresponding to the position of the elevator shaft,

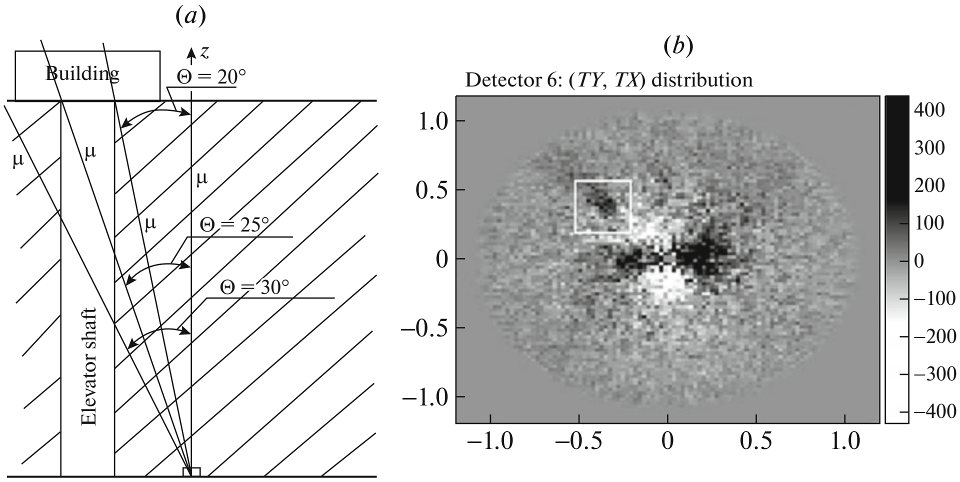

Fig. 3. (a) Scheme of the experiment in the mine at a depth of 30 m; (b) 2D-distribution (tx, ty) of muon flux at a depth of 30 m after subtracting of background, averaged by angle φ.

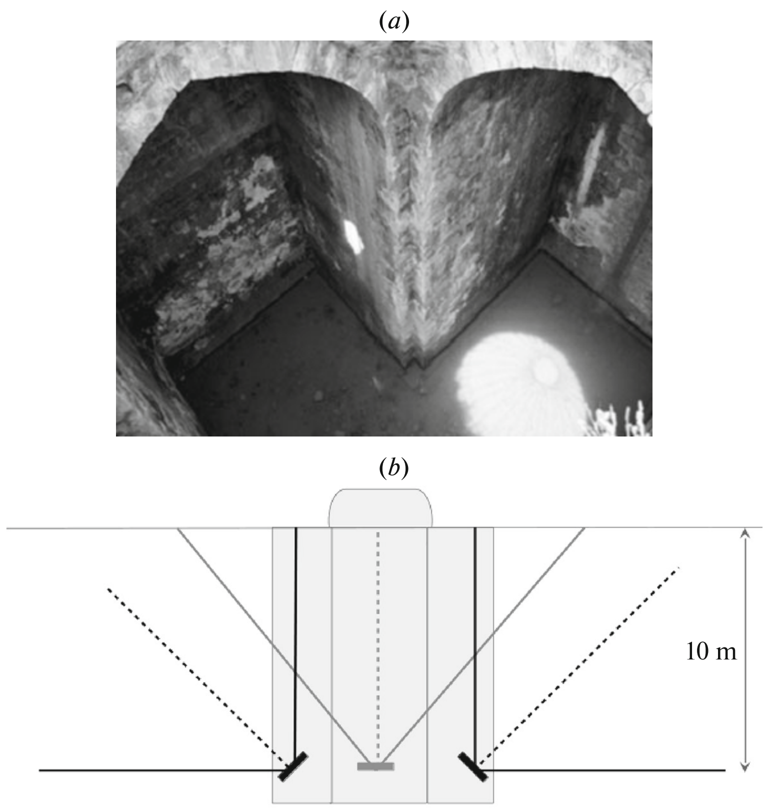

Fig. 4. (a) Internal view of the structure taken from the surface; (b) scheme of the detectors' installation inside the structure under study.

what demonstrates that the experiment successfully confirms validity of the method.

The first archaeological site in Russia studied by the muography method became the hidden under the earth surface archaeological site in the Naryn-Kala citadel (Derbent, Republic of Dagestan, Russia), one of UNESCO's world heritage objects [22].

The object of the study was an underground cross-shaped dome construction built of local shell-limestone, unfilled with soil and going to a depth of 10 m from the present ground level (Fig. 4). The building dates back to the IV–V century AD and is probably the oldest religious building on the territory of Russia. It is assumed that until the VII century

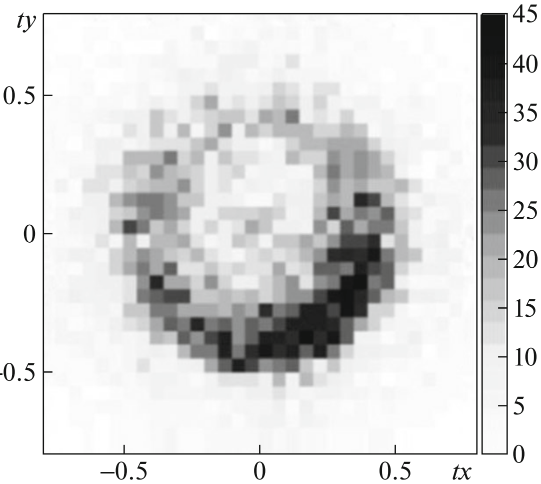

Fig. 5. Distribution of the registered muons in the angular variables tx and ty.

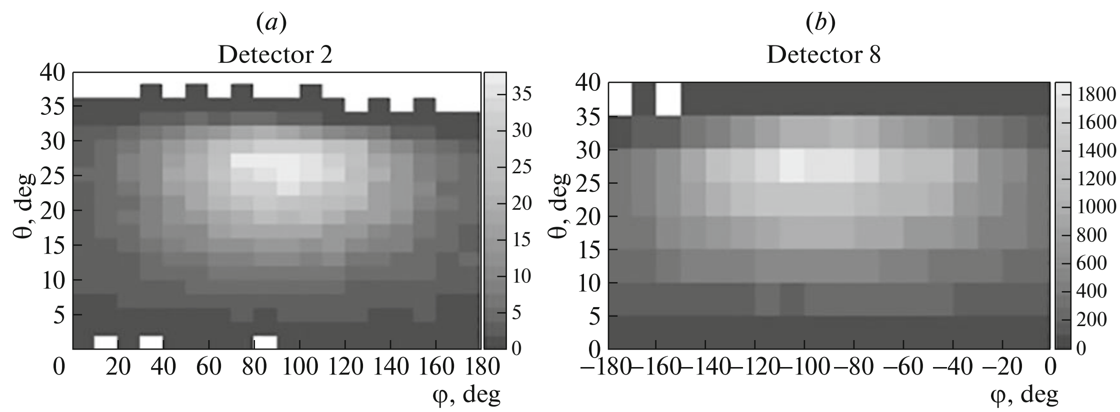

Fig. 6. Angular distributions of muon tracks in detectors 2 and 8 exposed in the basement of the Church of the Praise of the Mother of God: (a) in the form of two-dimensional histograms; (b) in the form of level lines.

AD, the structure under study was a ground-surface structure, but later it was filled in with soil from the outside and converted into a reservoir. The experiment was aimed to find out the possibility of studying this archaeological object by muography method, to determine the optimal exposure time, the number, size and location of detectors, and to obtain the first images of its structure using nuclear emulsions. The presence of voids, or conversely, denser areas in the walls and adjacent soil detected could confirm some of the existing hypotheses about its purpose.

In total, five emulsion detectors were used in this experiment, four of which were directed to the walls at an angle of 45°, and one was directed upwards to measure the vertical muon flux. Simulation of the passage of muons through the object with several probable values of the wall thickness and density was carried out and results of their registration by detectors were obtained. Figure 5 shows the experimental angular distribution of muons in one of the exposed detectors (D).

The distribution demonstrates a peak in the vertical flux region ($ty \sim -0.3$). The second peak from muons passing through the dome opening is not observed, since these muons enter detector D at angles outside the observation area ($\theta > 45°$). Some heterogeneity of the distribution near the observed peak may be conditioned by the uneven ground level around the structure and the presence of depressions up to 1 m or more. From the comparison of the obtained experimental distribution with the calculated one, one can conclude that the obtained result is the closest one to the simulation version with the wall parameters $L = 1.5$ m and $\rho = 2.65$ g/cm^3, where L is the wall thickness and ρ is its density. The experiment enabled to obtain the first images of the object in nuclear emulsions. Analysis of data, taken with emulsion detectors, demonstrated that non-uniformities seen in the angular distribution of cosmic muons may indicate some underground structures.

The series of test experiments made it possible to develop the necessary requirements for the emulsion quality, optimal detector designs and arrangement

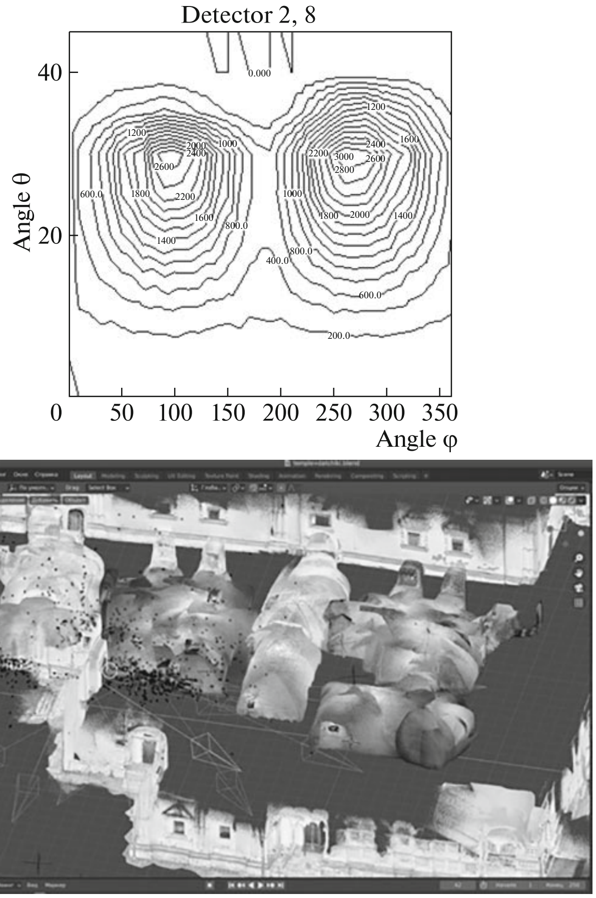

Fig. 7. Muon fluxes registered by emulsion detectors (arrows) added to 3D building model.

schemes, to upgrade equipment and computer programs for data processing and analysis at the PAVICOM automated measuring complex [23].

Currently, a new experiment is being carried out on the territory of another UNESCO cultural heritage site—the Holy Trinity Danilov Monastery in Pereslavl-Zalessky (Yaroslavl region, Russia). Among the tasks of the experiment is the study of hidden basements and unknown fragments of the foundation of one of the Monastery churches (the Church of the Praise of the Mother of God) [24]. Emulsion detectors placed in the accessible basements of the building are directed towards the expected unknown underground structures. The tracks of incoming muons are measured and analyzed, the differences in the angular distributions of muons could indicate the presence of features in the densities of structural elements of the building and underground. Figure 6 shows two representations of the experimental muon track distributions at the azimuthal (φ) and zenith (θ) angles in the coordinate system of detectors 2 and 8 (in total, 10 detectors installed in basements at a depth of about 2.5 m were used in the exposition). The distributions show "elongation" along the azimuth angle φ in the range $25° < \theta < 35°$, which indicates the presence of prolate horizontal cavities in the wall at the level of the ground floor (possibly air ducts). The obtained result demonstrates the high sensitivity of the method when using emulsion detectors.

To bind the experimental distributions to the building topography, its full-size computer model was created on base of the LIDAR survey. Its graphic representation is shown on Fig. 7. Arrows indicate fluxes of muons being registered by detectors in the basement.

3. CONCLUSIONS

Traditional methods of seismology, temperature survey, electromagnetic and gravimetric sounding used to study the internal structure of large objects are indirect and contain significant uncertainties associated with the interference of waves from different parts of the object under study. Muons of cosmic origin of high energies move in matter along almost straight trajectories and are devoid of this drawback. For this reason probing the large-scale geological and industrial objects with high-energy atmospheric muons is a promising alternative method. This method on the base of emulsion track detectors is successfully used in many countries (Japan, Italy, Switzerland, Canada, etc.), but in Russia it is at the initial stage of implementation. Results of the performed experiments show that Russian specialists have material, technical and intellectual resources for obtaining significant results on the base of muography, a new effective, highly economical and environmentally safe method for research in fields of geology, ecology, archeology, volcanology, flaw detection and other areas of scientific and practical activity.

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