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Simulation of Tunka-Grande and TAIGA-Muon scintillation facilities

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A planning for computer generated simulation of scintillation equipment based on the CORSIKA and Geant4 software packages is presented. Method developed to optimize the simulation process is presented. A possible approach for determining the mass composition of charged cosmic rays is discussed. Preliminary results of computer generated of the Tunka-Grande installation in the energy range 10−100 PeV are also presented.

Keywords: experimental complex TAIGA, cosmic rays, wide atmospheric showers, mass composition, CORSIKA, Geant4.

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Introduction. Scintillation facilities as a Part of the TAIGA Experimental Complex

The TAIGA experimental complex is located in the Tunkinskaya Valley (Republic of Buryatia, Russia) and is one of the most advanced modern experiments in the field of high-energy astrophysics and gamma-ray astronomy. It consists of 5 independent installations (TAIGA-HiSCORE, Tunka-133, Tunka-Grande, TAIGA-Muon, TAIGA-IACT), which study cosmic rays (CR) and gamma radiation by recording various components of extensive air showers (EAS).

The Tunka-Grande and TAIGA-Muon scintillation facilities consist of a combination of above-ground and underground scintillation counters, which allows them to record both the charged and muon components of EAS. One of the priority tasks of the facilities is to determine the mass composition of CRs, as well as to isolate astrophysical gamma quanta in the range of primary energies of 0.1−1000 PeV [1].

Historically, the first and most common method for determining the mass composition of CR is the study of the electron-photon and muon components of EAS. The information contained in the experimental data of the Tunka-Grande and TAIGA-Muon scintillation facilities on the number of secondary charged particles and, in particular, muons at the observation level, as well as their local densities at a certain distance from the shower axis, opens up possibilities for the implementation of this method.

1. Monte Carlo Problems of Scintillation Experiment Simulation

In order to determine the mass composition of the CL from the experimental data of scintillation facilities, it is necessary to conduct Monte Carlo simulation. At the first stage, it is planned to generate an array of artificial EAS in the CORSIKA [2] program. It is assumed that the rainfall will be carried out in the energy range CL 0.1–1000 PeV, within the zenith angles of arrival of EAS axis θ from 0 to 45° for the following primary particles: p, γ, He, CNO, Fe. QGSJET-II-04 [3], Sibyll 2.3d [4] and EPOS LHC [5] will be used as models of hadronic interactions at high energies. At least 10,000 events are expected to be generated for each of the variations. At the second stage, the response of scintillation facilities to secondary particles of artificial EAS will be simulated using the Geant4 [6] toolkit. In this case, the models of the Tunka-Grande and TAIGA-Muon [7] units developed earlier on the basis of this toolkit will be used.

The difficulty of performing simulations with programs such as CORSIKA in the case of the energy range 10–1000 PeV is that the requirements for computing resources and file storage are too high. In order to reduce the calculation time and data volume, it is planned to use two approximation methods — thinning and de-thinning. The first method is part of the standard CORSIKA [2] options and reduces the number of particles in the shower by assigning a weight w to the surviving particles to account for the energy of the excluded particles. The second method, developed and applied for the purpose of installing the Telescope Array [8], involves the reconstruction of the excluded sample of particles with a complete reconstruction of their parameters. This allows to reliably simulate the response of detectors to EAS events at the observation level.

To determine the mass composition of CR and gamma-hadron separation, it is proposed to use an approach related to the reconstruction of the number of muons in the EAS event, and their relative comparison with the general background of charged particles in this event. This approach is characterized by the fact that the number of muons depends on the type of primary nucleus, and in general, the heavier the nucleus, the greater the muon production in EAS. For example, at one level of primary energy, the number of muons in a gamma-quantum-initiated EAS is an order of magnitude lower than in a proton-initiated EAS. One of the possible ways to measure the number of particles of a particular type — to measure local densities at a distance of 200 m from the shower axis. However, large amounts of data, both experimental and model, are required to develop a method for identifying the mass composition for our plants. In the end, the solution of the above Monte Carlo simulation problem will allow us to make progress in this matter.

2. Preliminary Monte Carlo simulation results for Tunka-Grande

The figure shows the spatial distributions of the charged EAS particles recorded by the ground-based detectors of the Tunka-Grande facility in comparison with the preliminary simulation data for the three primary trains. Experimental distributions were obtained from data from 5 observation seasons (2017–2022). Model calculations were performed on the equipment of the „Irkutsk Supercomputer Center of the Siberian Branch of the Russian Academy of Sciences" [9] using CORSIKA version 7.7401 (model of hadronic interactions QGSJET-II-04) and Geant4 version 11.0.2. About 200–300 EAS events were simulated for each composition, and thinning and dethinning methods were used in the calculations. The following parameters were used for thinning: thinning coefficient $\varepsilon_{th} = 10^{-6}$, maximum weights for electrons and photons $w_{\max} = 10$ (10 PeV), $w_{\max} = 100$ (100 PeV) at $r > r_{\max}$, $r_{\max} = 100$ m. Muons and hadrons of EAS did not take part in thinning.

Fig. 1 shows that the simulated and experimental data are in fairly good agreement with each other. Computer simulations correctly reflect the process of EAS recording by the Tunka-Grande unit, considering the features of its design. The resulting simulation programs can be used to assess the quality of data recovery and test the methods used to reconstruct EAS events based on Tunka-Grande data. In addition, we can conclude that our approximation methods work correctly, and during simulation of EAS in the high-energy range, we can obtain reliable statistics with less computer resources.

Conclusion

At present, experimental data for 5 years of operation of the Tunka-Grande installation have been accumulated, and data collection has been started on the TAIGA-Muon installation, which is being constructed. The creation of an array of artificial EAS and simulation of the operation of scintillation facilities will make it possible to start studying the mass composition in the energy range of 0.1–1000 PeV.

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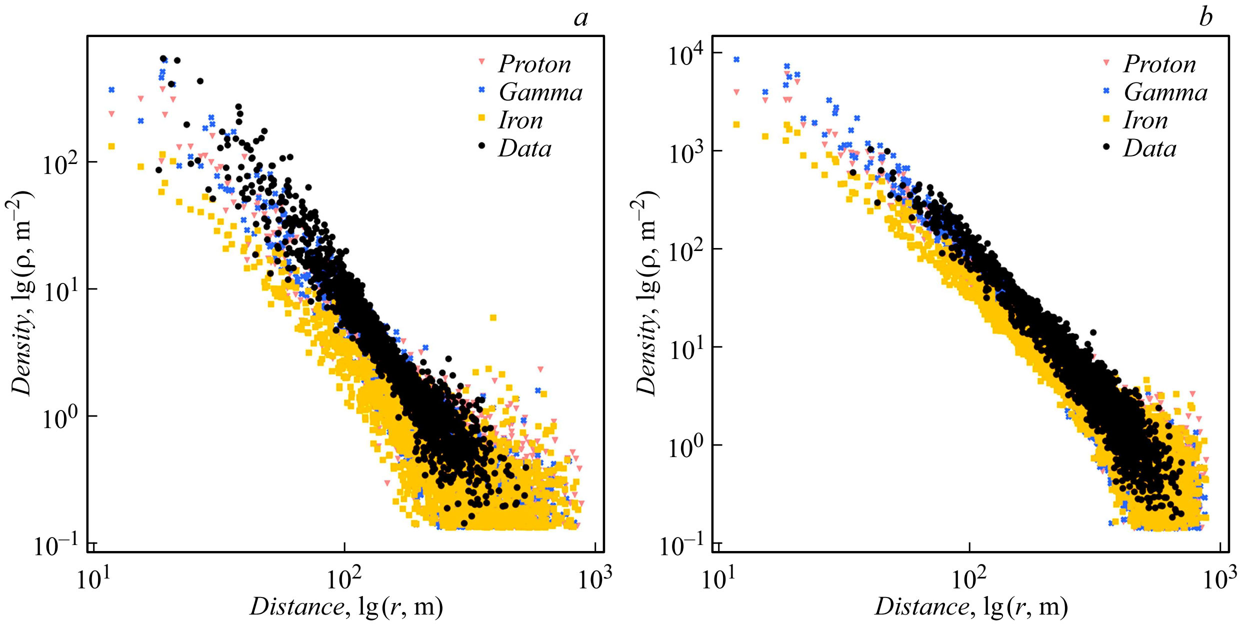

Spatial distributions of charged particles from the data of three simulated compositions (p, γ, Fe) and the Tunka-Grande experiment at the following parameters: a — $15.9 < \lg(E/eV) < 16.1$, $\theta < 3°$; b — $16.9 < \lg(E/eV) < 17.1$, $\theta < 3°$.

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Conflict of interest

The authors declare that they have no conflict of interest.

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