ISSN 1062-8738, Bulletin of the Russian Academy of Sciences: Physics, 2019, Vol. 83, No. 8, pp. 959–961. © Allerton Press, Inc., 2019.
Russian Text © The Author(s), 2019, published in Izvestiya Rossiiskoi Akademii Nauk, Seriya Fizicheskaya, 2019, Vol. 83, No. 8, pp. 1057–1060.

The Search for Diffuse Gamma Rays Using Data from the Tunka-Grande Experiment

R. D. Monkhoev[a, *], N. M. Budnev[a], D. M. Voronin[a], A. R. Gafarov[a], O. A. Gress[a], T. I. Gress[a], A. N. Dyachok[a], A. V. Zagorodnikov[a], V. L. Zurbanov[a], N. N. Kalmykov[b], Yu. A. Kazarina[a], S. N. Kiryuhin[a], E. E. Korosteleva[b], V. A. Kozhin[b], L. A. Kuzmichev[a, b], B. K. Lubsandorzhiev[c], N. B. Lubsandorzhiev[b], R. R. Mirgazov[a], E. A. Osipova[b], A. L. Pakhorukov[a], M. I. Panasyuk[b], L. V. Pankov[a], V. A. Poleschuk[a], E. G. Popova[b], V. V. Prosin[b], V. S. Ptuskin[d], A. A. Pushnin[a], Yu. A. Semeney[a], L. G. Sveshnikova[b], A. A. Silaev[b], A. A. Silaev, Jr.[b], A. V. Skurikhin[b], V. P. Sulakov[b], V. A. Tabolenko[a], A. Chiavassa[e], and C. Spiering[f]

[a] *Irkutsk State University, Institute of Applied Physics, Irkutsk, 664020 Russia*
[b] *Skobeltsyn Institute of Nuclear Physics, Moscow State University, Moscow, 119991 Russia*
[c] *Institute for Nuclear Research, Russian Academy of Sciences, Moscow, 142190 Russia*
[d] *Pushkov Institute of Terrestrial Magnetism, the Ionosphere, and Radio Wave Propagation, Russian Academy of Sciences, Moscow, 142190 Russia*
[e] *Department of Physics, Torino University and National Institute for Nuclear Physics (INFN), 10125 Torino, Italy*
[f] *Deutsches Eleknronen-Synchrotron (DESY), 22607 Hamburg, Germany*
**e-mail: makaay08@rambler.ru*

Received October 10, 2018; revised February 20, 2019; accepted April 26, 2019

Abstract—The Tunka-Grande array is part of an experimental complex located in the Tunka Valley (Republic of Buryatia, Russia) about 50 km from Lake Baikal. This complex also contains the Tunka-133 and Tunka-Rex arrays. The aim of this complex is to study the primary cosmic ray energy spectrum and mass composition in the energy range of 10^{16}–10^{18} eV, and to search for diffuse gamma rays in the energy range of 5×10^{16}–5×10^{17} eV. The design of the Tunka-Grande array and the procedure for reconstructing the parameters of extensive air showers (EASes) are described, and preliminary results are presented from the search for diffuse gamma rays with energies of more than 5×10^{16} eV.

DOI: 10.3103/S1062873819080306

INTRODUCTION

The study of cosmic rays (CR) of high and ultra-high energies is of great interest from the viewpoint of understanding their mechanisms and the nature of their origin, one of the most important tasks of modern astrophysics. Such high-energy radiation is registered using the only means currently possible, which are based on the property of primary particles to generate a cascade of secondary particles in the Earth's atmosphere, the so-called extensive air showers (EASes).

Most CRs are made up of primary nuclei, but considerable attention is also given to searching for primary gamma rays. Despite more than half a century of work in this direction, no astrophysical photons with energies above 10^{14} eV have been detected, and at present only restrictions on their flux have been established by numerous experimental data. Contributing greatly to such research have been the EAS-TOP [1], CASA-MIA [2], and KASCADE [3] facilities in the range of energies on the order of 3×10^{14}–5×10^{16} eV; the EAS-MSU [4] and KASCADE-Grande [3] facilities in the range of around 10^{16}–3×10^{17} eV; and the Haverah Park [5], AGASA [6], Yakutsk [7], Pierre Auger [8], and Telescope Array [9] facilities at energies above 10^{18} eV.

EXPERIMENTAL SETUP

The Tunka-Grande scintillation array [10] of the TAIGA (Tunka Advanced Instrument for Gamma Astronomy) observatory was put into service at the end of 2015 [11]. Its task is to study the energy spectrum and mass composition of cosmic rays in the energy range of 10^{16}–10^{18} eV in combination with the Tunka-133 [12] and Tunka-Rex [13] facilities, and to search for diffuse gamma radiation in the energy range of 5×10^{16}–5×10^{17} eV.

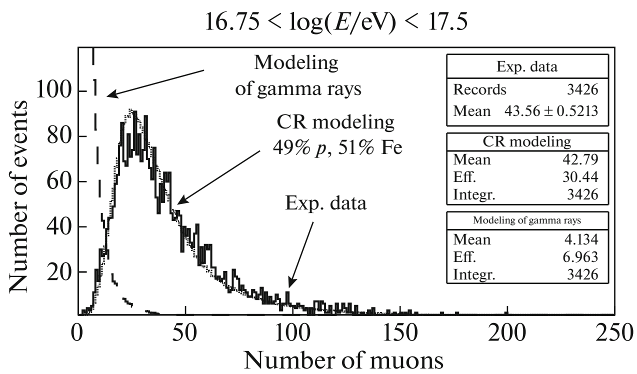

Fig. 1. Comparison of simulated and experimental data.

Tunka-Grande is an array of scintillation counters in 19 stations distributed over an area of 1 km^2. Each station is composed of two parts: one on the Earth's surface and one underground. The surface part, which consists of 12 counters, covers a total area of about 8 m^2 and detects all EAS charged particles at the level of the array. The second part, which consists of 8 counters with a total area of around 5 m^2, is under a layer of soil 1.5 m deep and is designed to separate the EAS muon component. Both parts of the array are in the immediate vicinity of each other.

The counter consists of a duralumin casing in the form of a truncated pyramid whose inner surface is covered with a thin diffuse-reflective layer of white enamel. An NE102A plastic scintillator in the shape of a flat plate 800 × 800 × 40 mm in size is placed in the casing along with a Philips XP-3462 photomultiplier tube (PMT). Early data counters were also been used successfully in the KASCADE-Grande and EAS-TOP experiments.

RECONSTRUCTING REGISTERED EVENTS

The reconstruction of registered events is taken to mean determining such parameters as coordinates x and y of the EAS axis in the plane of the array; zenith and azimuth angles θ and φ of EAS arrival; number N_e of all particles and number N_μ of charged particles; EAS age parameter s; particle density ρ_{200} at a characteristic distance of 200 m from the EAS axis; and primary particle energy E_o.

A function with parameter s is used as that of the lateral distribution (LDF) of electrons, depending on distance:

$$\rho_e(r) = N_e C_{\text{norm}} \left(\frac{r}{R_m}\right)^{s(r)-2} \left(1 + \frac{r}{R_m}\right)^{s(r)-4.5}, \quad (1)$$

where C_{norm} is the normalization factor, R_m = 80 m, and $s(r) = s_0 + a(r)$ [14].

The Greisen function, the parameters of which are determined from calculated data, is used as the muon LDF:

$$\rho_\mu(r) = N_\mu C_{\text{norm}} \left(\frac{r}{R_0}\right)^{-a} \left(1 + \frac{r}{R_0}\right)^{-b}, \quad (2)$$

where R_0 = 180 m, a = 0.61, b varies with an average of 2.6, and $\sigma(b)$ = 0.3.

A more detailed description of the modeling and event processing is described in [15].

The energy of a primary particle is determined from parameter ρ_{200} using the expression

$$\log(E_0, \text{eV}) = \log(\rho_{200}) \cdot 0.81 + 16.34. \quad (3)$$

This relation was obtained by comparing the reconstructed parameters of the joint events of the experimental data of the Tunka-Grande and Tunka-133 arrays for a period of around 176 h.

RESTRICTION ON THE INTEGRAL GAMMA RAY FLUX, RELATIVE TO THE INTEGRAL COSMIC RAY FLUX

One of the most promising approaches to isolating events from primary gamma rays from the CR background is studying the EAS muon component, since the number of muons in a shower generated by a gamma quantum is an order of magnitude less than in the hadronic shower. The main aim is therefore to search for non-muon events, or events depleted in muons. This in turn requires Monte Carlo modeling of EASes, along with selecting and comparing experimental data. Showers from different primary particles were therefore generated for the ground and underground parts of the scintillation stations: gamma rays, protons, and iron nuclei. Modeling was done for four energy values ($\log(E_0, \text{eV})$ = 16.75, 17, 17.25, 17.5) and for three values of the zenith angle (θ = 0°, 30° and 45°). A total of 1,000 showers were modeled in each case. The CORSIKA package (Version 7.6300) was chosen as the software. Hadron interactions at low energies were calculated using the GHEISHA model; high-energy interactions were processed with the QGSJET-II-04 model.

Our selection of experimental data met a number of criteria. The stations had to be in operating condition during observations, the reconstructed zenith angle had to be ≤45°, the distance between the reconstructed position of the EAS axis and the array center had to be <400 m, and the reconstructed energy of a primary particle had to be $\log(E_0, \text{eV}) \geq 16.75$. The total operating time of the installation was in this case 4421 hours, and 3552 events were selected.

Figure 1 compares the number of muons registered by the array for modeled and experimental data. The primary composition of the modeled cosmic rays (49% protons and 51% iron nuclei) was selected on the basis of results from the Tunka-133 array [16].

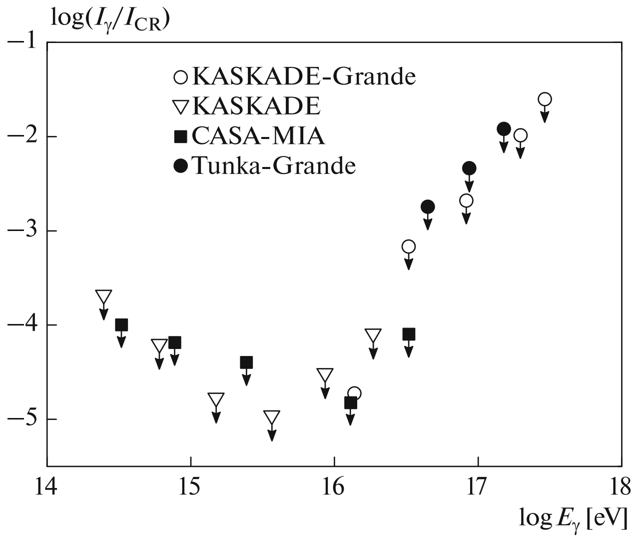

Fig. 2. Fraction of gamma ray flux, relative to the cosmic ray flux.

In our analysis of these experimental data, the maximum possible number of registered muons for candidates in photon EASes was set at a level of 1 particle when $\log(E_0,\ \mathrm{eV}) \geq 16.75$, at a level of 3 when $\log(E_0,\ \mathrm{eV}) \geq 17$, and at a level of 6 when $\log(E_0,\ \mathrm{eV}) \geq 17.25$. However, no events were detected under these conditions.

The upper limit on the fraction of the integral gamma ray flux relative to the integral cosmic ray flux is given by the expression [2]

$$\frac{I_\gamma}{I_{CR}} < \frac{N_{90}}{N_{tot}\varepsilon_\gamma}\left(\frac{E_{CR}}{E_\gamma}\right)^{-\beta+1}, \qquad (4)$$

where N_{tot} is the total number of events; N_{90} is the 90% CR upper limit on the number of detected events (the Feldman–Cousins approach for the Poisson distribution [17]); E_{CR} and E_γ are the average energy of CRs and gamma quanta; ε_γ is the efficiency of detected events from gamma quanta; and β is the spectral index of the integral flux of cosmic rays.

Figure 2 compares the obtained limitations to results from the KASCADE-Grande, KASCADE, and CASA-MIA experiments.

CONCLUSIONS

The results presented for the restriction on the flux of diffuse gamma rays according to the Tunka-Grande array are obviously worse than those obtained from the EAS-MSU and KASCADE-Grande experiments, due to the relatively short period of operation. The array has great potential, however, and the upper limits on the 5×10^{16}–5×10^{17} eV range of flux energies will be substantially improved in the coming years.

ACKNOWLEDGMENTS

This work was performed on equipment at the Tunka Astrophysical Center for Collective Use (TACCU) as part of an agreement with the RF Ministry of Education and Science, unique identifier RFMEFI59317X0005. All calculations were performed on HPC-cluster "Akademik V.M. Matrosov" [18].

FUNDING

This work was supported by the RF Ministry of Education and Science, project nos. 3.9678.2017/BC, 3.904.2017/PC, 3.6787.2017/ITR, and 1.6790.2017/ITR; and by the Russian Foundation for Basic Research, project nos. 16-02-00738, 17 02-00905, 18-32-00460.

REFERENCES

1. Aglietta, M., Alessandro, B., Antonioli, P., et al., *Astropart. Phys.*, 1996, vol. 6, p. 71.
2. Chantell, M.C., Covault, C.E., Cronin, J.W., et al., *Phys. Rev. Lett.*, 1997, vol. 79, p. 1805.
3. Apel, W.D., Arteaga-Velazquez, J.C., Bekk, K., et al., *Astrophys. J.*, 2017, vol. 848, p. 1.
4. Fomin, Yu.A., Kalmykov, N.N., Karpikov, I.S., et al., *Phys. Rev. D*, 2017, vol. 95, p. 123011.
5. Ave, M., Hinton, J.A., Vazquezet, R.A., et al., *Phys. Rev. Lett.*, 2000, vol. 85, p. 2244.
6. Shinozaki, K., Chikawa, M., Fukushima, M., et al., *Astrophys. J.*, 2002, vol. 57, p. L117.
7. Glushkov, A.V., Gorbunov, D.S., Makarov, I.T., et al., *Phys. Rev. D*, 2010, vol. 82, p. L117.
8. Bleve, C., Proc, p. 34.
9. Rubtsov, G.I., Fukushima, M., Ivanov, D., et al., *Proc. 34th Int. Cosmic Ray Conf.*, Hague, 2015, p. 331.
10. Monkhoev, R.D., Budnev, N.M., Chiavassa, A., et al., *J. Instrum.*, 2017, vol. 12, p. 06019.
11. Kuzmichev, L.A., Astapov, I.I., Bezyazeekov, P.A., Boreyko, V., Borodin, A.N., Budnev, N.M., Wischnewski, R., Garmash, A.Y., Gafarov, A.R., Gorbunov, N.V., Grebenyuk, V.M., Gress, O.A., Gress, T.I., Grinyuk, A.A., Grishin, O.G., et al., *Phys. At. Nucl.*, 2018, vol. 81, p. 497.
12. Prosin, V.V., Berezhnev, S.F., Budnev, N.M., et al., *EPJ Web Conf.*, 2016, vol. 121, p. 03004.
13. Schröder, F.G., Bezyazeekov, P.A., Budnev, N.M., et al., *Nucl. Instrum. Methods Phys. Res., Sect. A*, 2016, vol. 824, p. 652.
14. Kalmykov, N.N., Kulikov, G.V., Sulakov, V.P., and Fomin, Yu.A., *Bull. Russ. Acad. Sci.: Phys.*, 2013, vol. 77, p. 626.
15. Budnev, N.M., Ivanova, A.L., Kalmykov, N.N., Kuz'michev, L.A., Sulakov, V.P., and Fomin, Yu.A., *Moscow Univ. Phys. Bull.*, 2014, vol. 69, p. 357.
16. Berezhnev, S.F., Besson, D., Budnev, N.M., et al., *Proc. 32nd Int. Cosmic Ray Conf.*, Beijing, 2011, vol. 1, p. 209.
17. Feldman, G.J. and Cousins, R.D., *Phys. Rev. D*, 1998, vol. 57, p. 3873.
18. http://hpc.icc.ru.

Translated by E. Seifina