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Energy Spectrum of Primary Cosmic Rays According to the Data of the TAIGA Astrophysical Complex

V. V. Prosin[a, *], I. I. Astapov[d], P. A. Bezyazeekov[b], E. A. Bonvech[a], A. N. Borodin[c], N. M. Budnev[b], A. V. Bulan[a], D. V. Chernov[a], A. Chiavassa[k], A. N. Dyachok[b], A. R. Gafarov[b], A. Yu. Garmash[e, h], V. M. Grebenyuk[c, j], E. O. Gress[b], O. A. Gress[b], T. I. Gress[b], A. A. Grinyuk[c], O. G. Grishin[b], M. A. Iliushin[b], A. D. Ivanova[b], A. L. Ivanova[b, e], N. N. Kalmykov[a], V. V. Kindin[d], S. N. Kiryuhin[b], R. P. Kokoulin[d], N. I. Kolosov[b], K. G. Kompaniets[d], E. E. Korosteleva[a], V. A. Kozhin[a], E. A. Kravchenko[e, h], A. P. Kryukov[a], L. A. Kuzmichev[a], A. A. Lagutin[i], M. V. Lavrova[c], Yu. E. Lemeshev[b], B. K. Lubsandorzhiev[f], N. B. Lubsandorzhiev[a], S. D. Malakhov[b], R. R. Mirgazov[b], R. A. Monkhoev[b], E. A. Okuneva[a], E. A. Osipova[a], A. L. Pakhorukov[b], A. Pan[c], A. D. Panov[a], L. V. Pankov[b], A. A. Petrukhin[d], D. A. Podgrudkov[a], E. G. Popova[a], E. B. Postnikov[a], V. S. Ptuskin[g], A. A. Pushnin[b], R. I. Raikin[i], A. V. Razumov[a], E. V. Rjabov[b], G. I. Rubtsov[f], V. S. Samoliga[b], I. Satyshev[c], A. Yu. Sidorenkov[f], A. A. Silaev[a], A. A. Silaev, Jr.[a], A. V. Skurikhin[a], A. V. Sokolov[e], L. G. Sveshnikova[a], V. A. Tabolenko[b], A. B. Tanaev[b], B. A. Tarashansky[b], M. Yu. Ternovoy[b], L. G. Tkachev[c, j], N. A. Ushakov[f], A. Vaidyanathan[e], N. V. Volkov[i], P. A. Volchugov[a], D. M. Voronin[f], I. I. Yashin[d], A. V. Zagorodnikov[b], and D. P. Zhurov[b]

[a] *Skobeltsyn Institute of Nuclear Physics, Moscow State University, Moscow, 119991 Russia*
[b] *Applied Physics Institute, Irkutsk State University, Irkutsk, 664003 Russia*
[c] *Joint Institute for Nuclear Research, Dubna, 141980 Russia*
[d] *National Research Nuclear University MEPhI, Moscow, 115409 Russia*
[e] *Novosibirsk State University, Novosibirsk, 630090 Russia*
[f] *Institute for Nuclear Research, Russian Academy of Sciences, Moscow, 117312 Russia*
[g] *Puskov Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation, Russian Academy of Sciences, Moscow, 108840 Russia*
[h] *Budker Institute of Nuclear Physics, Siberian Branch, Russian Academy of Sciences, Novosibirsk, 630090 Russia*
[i] *Altai State University, Barnaul, 656049 Russia*
[j] *Dubna State University, Dubna, 141980 Russia*
[k] *Dipartimento di Fisica Generale, Universita di Torino and INFN, Turin, 10124 Italy*
**e-mail: v-prosin@yandex.ru*

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Abstract—The more correct recalculation from the measured Cherenkov light fluxes at distances of 200 (Q200) and 100 (Q100) m from the Extensive Air Shower (EAS) core to the energy of the primary particle has been developed using the results of M-C simulation by the CORSIKA code, assuming a light primary composition of cosmic rays. Using the new conversion expressions, a differential energy spectrum was obtained according to the data of the Tunka-133 array for 7 years of operation and the TAIGA-HiSCORE array for 2 years of operation.

Keywords: extensive air shower, Cerenkov light flux, primary particle energy spectrum

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INTRODUCTION

The energy spectrum and mass composition of primary cosmic rays are the main characteristics that can be obtained by studying extensive air showers (EAS). According to the latest data on the depth of shower maximum [1], the composition in the entire measured energy range turned out to be lighter than previously assumed [2]. Based on the simulation results for a light composition, new conversion formulas from Cherenkov light flux densities at distances of 200 and 100 m to a primary particle energy were developed, considering air shower zenith angles. The corrected spectrum is presented in the energy range from 2×10^{14} to 2×10^{18} eV.

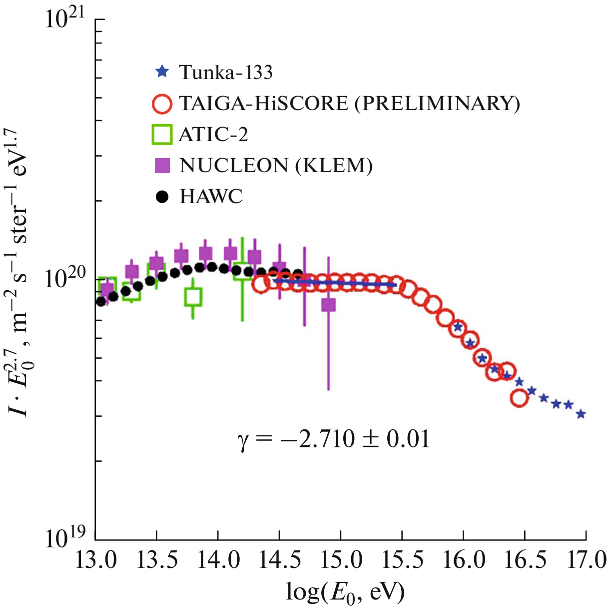

Fig. 1. Differential all particles energy spectrum obtained by recalculation from Q100 according to the TAIGA-HiSCORE array. For comparison, the spectra obtained from direct measurements on a balloon [8], a satellite [9], and in the mountains [10] are presented.

BRIEF REVIEW OF THE ARRAYS

Several arrays detecting EAS Cherenkov light were consistently built in Tunka Valley. The most productive of them were Tunka-25 (2000–2005) [3], which consisted of 25 detectors with a sensitive area of 0.1 m^2 each, occupying a total area of approximately 0.1 km^2, and Tunka-133 (2009–2017) [4], which ultimately consisted of 175 detectors with a sensitive area of 0.03 m^2, occupying an area of about 3 km^2. The Tunka-133 array was collecting data during 350 clear moonless nights (2175 h of observations in total). Their modern successor is the TAIGA-HiSCORE array [1], which is part of the TAIGA experimental complex [5]. A single TAIGA-HiSCORE station has a sensitive area of 0.5 m^2. Currently, the array includes 120 stations gathered into 4 clusters for data collection. This paper presents data obtained using 67 stations (the first two clusters) during 135 clear moonless nights in the 2019–2020 and 2020–2021 seasons. The total data collection time was 327 h.

AIR SHOWER PARAMETERS RECONSTRUCTION

The reconstruction of air shower parameters (zenith θ and azimuth φ angles, coordinates of the EAS core on the observation plane, and steepness of the LDF) for the Tunka-133 array is described in [4]. The same technique is used to process the data from the TAIGA-HiSCORE array [1]. To reconstruct the energy in [4], we used the recalculation from the parameter Q200, which is a flux of Cherenkov light at a core distance of 200 m. It was assumed that this parameter does not depend on the shower zenith angle. For the TAIGA-HiSCORE array in the previous work [6], the average light flux density parameter for two stations closest to a shower core was used for energy reconstruction. This parameter provided decreasing of the energy threshold. However, further analysis of the calculations showed that the better precision at the same threshold can be reached using the light flux density at the EAS core distance of 100 m, which can be measured at all registered events. This parameter for fixed particle energy depends on shower zenith angle. To improve the accuracy of energy measurement by Q200, zenith dependence is also considered for the parameter Q200.

In all subsequent formulas, the Cherenkov light flux is expressed in the units of [photon cm^{-2}]. The conversion formulas for recalculation from the measured zenith angle θ to 0° for artificial showers obtained using the CORSIKA simulation code for a primary mass composition of an equal number of protons and helium nuclei, are:

$$\log(\mathrm{Q100}(0)) = \log(\mathrm{Q100}(\theta)) + (\sec\theta - 1) \times (1.25 - 0.083\log(\mathrm{Q100}(\theta)), \quad (1)$$

$$\log(\mathrm{Q200}(0)) = \log(\mathrm{Q200}(\theta)) + (\sec\theta - 1) \times (0.244 - 0.047\log(\mathrm{Q200}(\theta)). \quad (2)$$

Recalculation to the primary particle energy E_0:

$$\log(E_0/\mathrm{GeV}) = 0.88\log(\mathrm{Q100}(0)) + 5.14, \quad (3)$$

$$\log(E_0/\mathrm{GeV}) = 0.96\log(\mathrm{Q200}(0)) + 5.67. \quad (4)$$

EXPERIMENTAL ENERGY SPECTRUM

The experimental energy reconstruction constant differs from that described in the previous section, because the actual transparency of the atmosphere differs from night to night and from that used in CORSIKA. The conversion to energy is corrected according to experimental data. At first, we obtain the integral energy spectrum for single night using expressions 3 or 4. Then we normalize this spectrum to the reference energy spectrum measured in the QUEST experiment [7]. The average difference of the normalization constant obtained for each night from that in expressions 3 or 4 is 0.03. The standard deviation of the difference is about 0.01.

The differential energy spectrum obtained by recalculation from Q100 according to the TAIGA-HiSCORE data, multiplied by the energy to the power of 2.7 (Fig. 1), is compared with the spectra from direct measurements on a balloon [8], a satellite [9], and in the mountains [10]. One can see good agreement of all spectra in the 200–300 TeV energy range, despite the

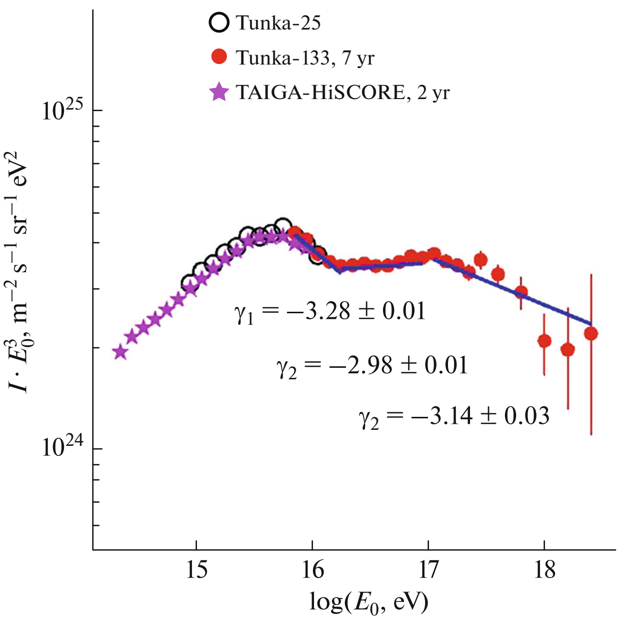

Fig. 2. Differential all particles energy spectrum by the data of the Tunka-133 array, obtained by recalculation from Q200 using formulas (2 and 4). For comparison, the spectra are given according to the data of the TAIGA-HiSCORE and Tunka-25 arrays [3].

significant difference in the experimental technique. Figure 2 shows the corrected spectrum of the Tunka-133 array compared to the spectra of the TAIGA-HiSCORE and Tunka-25 arrays. All kinds of spectrum are multiplied by energy to the power of 3.0. Two significant deviations from the power law are noticeable in the spectrum: flattening at the energy of 2×10^{16} eV and steepening at about 10^{17} eV (the second "knee").

CONCLUSIONS

The arrays for air shower registration by Cherenkov light made it possible to obtain the energy spectrum of primary cosmic rays in a wide energy range from 2×10^{14} to 2×10^{18} eV using a unified technique.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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