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Depth of the Maximum of Extensive Air Showers (EASes) and the Mean Mass Composition of Primary Cosmic Rays in the 10^{15}–10^{18} eV Range of Energies, According to Data from the TUNKA-133 and TAIGA-HiSCORE Arrays for Detecting EAS Cherenkov Light in the Tunkinsk Valley

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Abstract—A corrected energy dependence of the depth of the maximum in the wide range of energies 10^{15} to 10^{18} eV is obtained using data collected at the Tunka-133 facility over 7 years of operation (2009–2017) and the TAIGA-HiSCORE facility in the 2019–2020 season. At the highest energies, our results match those of the Pierre Auger observatory. The results are converted to parameter $\langle \ln A \rangle$, which characterizes the mean EAS composition.

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INTRODUCTION

The Tunka-133 facility [1] acquired data over seven winter seasons in 2009–2014 and 2015–2017. Information was gathered for 350 clear moonless nights. The total time of data acquisition is 2175 h.

The TAIGA-HiSCORE [2] facility is in a state of permanent expansion and modernization. In this work, we present data obtained using 59 stations of the

† Deceased.

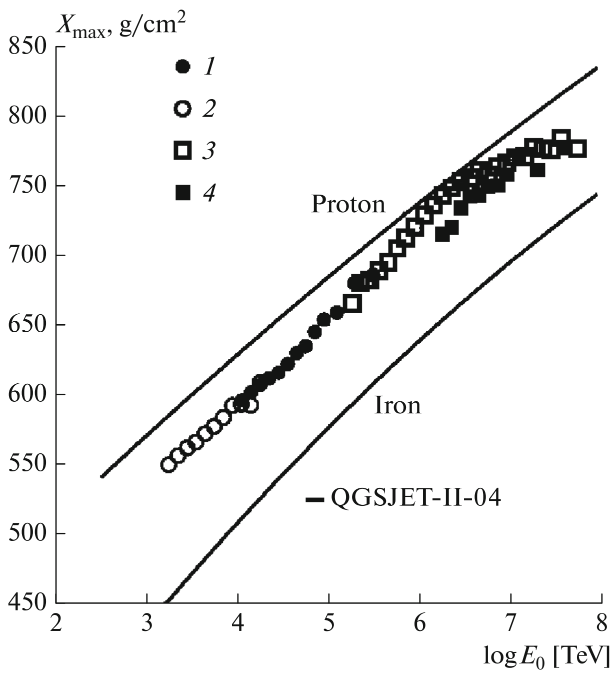

Fig. 1. Mean depth of the EAS maximum: (*1*) Tunka-133 (2009–2017), (*2*) TAIGA-HiSCORE (2019–2020), (*3*) Pierre Auger Observatory (2019), and (*4*) Telescope Array (2018).

first stage, forming two clusters (32 stations in the first and 27 stations in the second) for 69 clear moonless nights in 2019–2020. The total time of data acquisition is 327 h. The experimental data are processed using programs in which all functions of approximation and conversion are obtained by analyzing artificial events generated using the CORSIKA program for the 10^{14} to 10^{18} eV range of energies [1]. The direction of arrival, the coordinates of the axis on the plane of observation, the energy of primary particles, and the slope of the SDF of Cherenkov light are reconstructed for each shower.

PROCESSING DATA AND RECONSTRUCTING EAS PARAMETERS

Data processing for the Tunka-133 facility was described in [1].

The main EAS parameters were reconstructed using data from the TAIGA–HiSCORE facility using the same algorithms and fitting functions as with Tunka-133.

New modeling using the CORSIKA software for a wider range of energies has confirmed that the slope of the spatial distribution function is uniquely determined only by the thickness of the atmosphere between the experimental setup and the depth of the EAS maximum:

$$\Delta X_{max} = X_0/\cos\theta - X_{max} \quad (1)$$

regardless of the energy, shower zenith angle θ, and the type of the primary nucleus. Here, X_0 is the depth of the atmosphere.

The choice of the SDF parameter, which is sensitive to depth on the one hand, and is measured in each event at our facilities in a wide range of energies on the other, led to parameter $P = Q(80)/Q(200)$.

We use results from calculations for showers generated from protons and iron with energies of 10^{15} to 10^{18} eV and zenith angles of 0° and 30°. The dependence of ΔX_{max} on parameter P is fitted by two linear segments:

$$\Delta X_{max} = 1007 - 129.5P,\ [\mathrm{g/cm^2}]\ \text{ for }\ P \le 3.724, \quad (2)$$

$$\Delta X_{max} = 845 - 86.0P,\ [\mathrm{g/cm^2}]\ \text{ for }\ P > 3.724. \quad (3)$$

The depth of maximum X_{max} of an event with zenith angle θ is determined from X_{max} using inverting formula (1) for $X_0 = 965$ g/cm^2.

MEAN DEPTH OF THE EAS MAXIMUM

The new parameter of the SDF slope was used to analyze data from both the Tunka-133 and TAIGA-HiSCORE facilities. For the Tunka-133 facility, showers were sampled in a circle with a radius of 450 m, zenith angles of 0–30°, and energies above 10^{16} eV. Based on these criteria, we selected 69000 showers. For the TAIGA-HiSCORE facility, showers were sampled in a circle with a radius of 225 m lying in the first cluster and in a circle with a radius of 300 m in the first and second clusters, with zenith angles 0°–30° and energies above 1.5×10^{15} eV. Based on these criteria, we selected 167000 events. The mean depths of the EAS maximum obtained for the two facilities versus the energy of a primary particle are shown in Fig. 1. Despite the difference between their geometries, the data from both facilities agree well with one another, providing a wide range of energies from 10^{15} to 10^{18} eV. Our experimental data are compared to results from direct measurements of the maximum depth obtained by observing the light of EAS ionization at the Auger (PAO) [3] and Telescope Array (TA) [4] facilities. Good agreement is observed between our data and that of the PAO at an energies of around 3×10^{17} eV.

All experimental results are compared to theoretical curves calculated using the QGSJET-II-04 model [5, 6] for primary protons and iron nuclei. Note that this model gives the highest position of the maximum among all of those currently used. At an energy of 10^{17} eV, the EPOS-LHC model [6] yields a maximum ~10 g/cm^2 deeper, while the SIBYLL 2.3c model [6] gives a maximum ~25 g/cm^2 deeper than QGSJET-II-04.

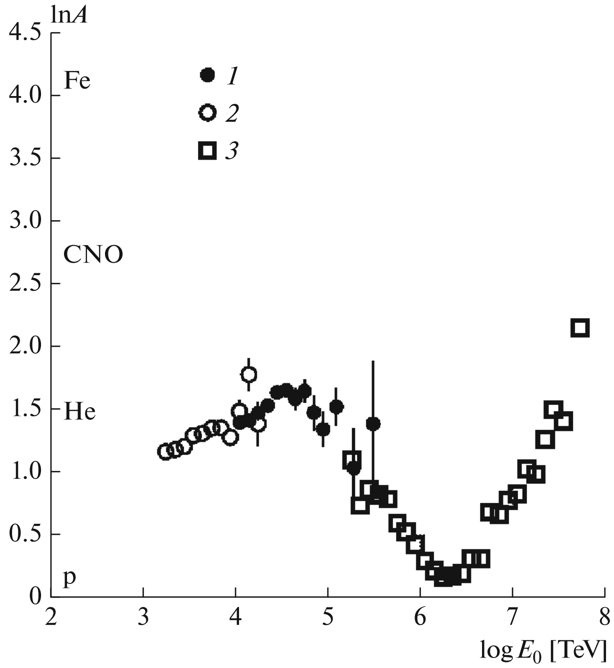

Fig. 2. Results from converting the mean depth of the EAS maximum to parameter $\langle \ln A\rangle$ according to the QGSJET-II-04 model: (*1*) Tunka-133 (2009–2017), (*2*) TAIGA-HiSCORE (2019–2020), and (*3*) Pierre Auger Observatory (2019).

MEAN COMPOSITION OF COSMIC RAYS

The mean composition of primary cosmic rays for ground-based facilities detecting EASs with poor charge resolution is traditionally characterized by parameter $\langle nA\rangle$, the mean value of the logarithm of the atomic number of primary nuclei. This parameter is related linearly to the mean depth of the EAS maximum, so conversion to the mean composition for all facilities (including Auger) is done via linear interpolation between calculations of the maximum depth for protons and iron. Figure 2 shows the results of conversion from the mean depth of the maximum to the mean composition according to the QGSJET-II-04 model. Qualitatively, the behavior of the mean mass composition repeats the one described in [7]. The composition becomes heavier in the 10^{15}–5×10^{16} eV range of energies and lighter upon a further increase in energy. However, the mean composition throughout the considered range of energies is estimated to be much lighter than in [7]. Earlier, it was closer to the group of CNO nuclei in the maximum of the considered curve, but the maximum now corresponds better to helium (He) nuclei. New estimates of the composition are in much better agreement with direct measurements of the maximum depth at the PAO than earlier ones.

It should be noted that the EPOS-LHC model [6] provides a simultaneous increase in both our estimates of $\langle \ln A\rangle$ (at 5×10^{16} eV by 0.35) and estimates of this parameter at PAO. The Sibill2.3c model [6] also raises the estimate of $\langle \ln A\rangle$ at 5×10^{16} eV by 0.60 with a simultaneous increase in the estimate of this parameter at the PAO.

The results of our work require further refinement using model calculations.

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REFERENCES

1. Budnev, N.M., Chiavassa, A., Gress, O.A., et al., *Astropart. Phys.*, 2020, vol. 117, 102406.
2. Prosin, V., Astapov, I., Bezyazeekov, P., et al., *EPJ Web Conf.*, 2019, vol. 210, 01003.
3. Yushkov, A. (on behalf of the Pierre Auger Collab.), *Proc. 36th Int. Cosmic Ray Conf.*, Madison, 2019, 482.
4. Abbasi, R.U. et al. (Telescope Array Collab.), *Astrophys. J.*, 2018, vol. 858, p. 76.
5. Ostapchenko, S. and Bleicher, M., *Phys. Rev. D*, 2016, p. 93, 051501.
6. Pierog, T., *EPJ Web. Conf.*, 2019, vol. 208, 02002.
7. Prosin, V.V., Berezhnev, S.F., Budnev, N.M., et al., *EPJ Web Conf.*, 2016, vol. 121, 03004.

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