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ELEMENTARY PARTICLES AND FIELDS
Experiment

Particles of Primary Cosmic Radiation Generating Extensive Air Showers of Energy above 10^{20} eV in the Atmosphere

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Abstract—In order to construct the energy spectrum on the basis of data from the Yakutsk array, a method similar to that employed at the AGASA array is applied in addition to the standard approach based on experimental procedures. Moreover, a new, original, method underlying the calculation of the spectrum in the region of energies above 10^{20} eV is used to estimate energies. In order to compare data obtained at different arrays, it is proposed to harness the universal spectrum based on HiRes data. Within the QGSJET2 model, it is shown that a shower of energy 2×10^{20} eV was observed at the Yakutsk array. In the same energy region (above 2×10^{20} eV), the AGASA array recorded four showers, while the Fly's Eye array and Pierre Auger Observatory (PAO) recorded one shower each. These data do not confirm the conclusion that the flux of primary-cosmic-ray particles decreases because of the Greisen—Zatsepin—Kuzmin effect.

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1. INTRODUCTION

Investigation of the energy spectrum of cosmic rays in the region of ultrahigh energies—in particular, investigation of its special features in various energy regions—is of considerable interest. First, there arises the possibility for developing the astronomy of ultrahigh-energy cosmic rays [1], since protons of primary cosmic rays in the region of energies above 5×10^{19} eV undergo a deflection from the direction to the source through a relatively small angle (several degrees) under standard assumptions on galactic and intergalactic magnetic fields. Searches for possible correlations between the arrival directions of extensive air showers (EAS) and directions to remote sources {such as quasars [2], BL Lacertae objects (BL Lac for short) [3], and Seyfert galaxies [4]} are an important implementation of this possibility. Second, a special feature in the form of a transition from galactic to intergalactic rays must be observed in the energy spectrum, since the Milky Way Galaxy does not confine ultrahigh-energy particles. The observed excess of cosmic rays in the energy range 5×10^{18}–5×10^{19} eV (bump) is usually treated as the region of such a transition in the case of a complex composition of primary cosmic rays. If, however, primary cosmic rays are formed by protons (protonic composition), then this transition is shifted, possibly by about 10^{18} eV, in which case the spectrum observed in the energy range 10^{18}–5×10^{19} eV, including the excess in question, is explained by the change in the exponent of the spectrum because of the production of electron—positron pairs in the interaction of protons with cosmic-microwave-background radiation (CMBR or relic photons) [5]. Therefore, investigation into the nature of primary-cosmic-ray particles—in particular, a determination of the fraction of primary photons [6]—is of particular interest. We note that data from [7] on the complex composition of primary cosmic rays are incompatible with the observation of their protonic composition in [8]. The reports in [7, 8] on the observation of a sharp decrease in the cosmic-ray flux at energies above about 6×10^{19} eV in accordance with the results of Greisen [9] and Zatsepin and Kuzmin [10] (GZK effect), who predicted this effect as a consequence of a large energy loss of cosmic-ray protons because of pion production in the interaction of these protons with CMBR photons, are of greatest interest. If primary cosmic radiation is dominated by nuclei (according to [7]), then the interpretation of this decrease in the flux must be different. We note

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that data from [11] do not provide an indication of a decrease in the cosmic-ray flux because of the GZK effect. The spectrum in [11] was obtained by using estimates of energy that were found within the QGSJET1 model on the basis of the readings of scintillation detectors. Fluorescent light was used in [8] to calibrate ground-based detectors (water tanks), but, as was indicated in [12], theoretical estimates of energy obtained for these tanks on the basis of various models are approximately 1.5 times larger than values found upon the calibration. At the Yakutsk array [13], signals are measured in ground-based scintillation detectors, in underground detectors recording shower muons, and in detectors for Cherenkov light from particles of air showers.

A standard approach to estimating EAS energies on the basis of experimental procedures is used at the Yakutsk array. This approach can be described briefly as follows. First, the zenith (θ) and azimuthal (φ) angles of the arrival direction are determined for each individual shower on the basis of the readings of time detectors. This is done within the plane-shower-front model. The shower-axis coordinates in the detector plane are determined by using a lateral distribution whose parameters are fitted rather than being thought to be known. For a shower whose zenith angle θ has been found, a signal is then determined as the energy deposited in scintillation detectors by shower electrons, positrons, photons, and muons at a distance of 600 m from the shower axis, $s(600,\theta)$. The next step consists in rescaling the signal $s(600,\theta)$ to its value for the respective vertical shower on the basis of the relation

$$s(600) = s(600,\theta)\exp(\Delta x/\lambda),$$

where $\Delta x = x_0(\sec\theta - 1)$, with x_0 being the observation-level depth, and λ is the mean value of the absorption range as determined by cutting the spectra of signals by equal-intensity lines. Finally, the following formula is used to estimate the shower energy E (in eV units):

$$E = as^b(600). \tag{1}$$

On the basis of the calibration of the signal for vertical showers by Cherenkov light, the coefficients in (1) were found to be $a = 4.8\times10^{17}$ eV and $b \approx 1$ (in order to avoid encumbering the presentation, we have omitted the errors). That all of the steps of the standard method rely on experimental data is its indisputable advantage. Theoretical estimates of energy on the basis of signals in ground-based scintillation detector stations differ substantially from experimental estimates obtained in calibrating these signals on the basis of readings of Cherenkov light detectors. Between two realizations (that in [7] and that in [8]) of the fluorescence method, there is also a difference of about 18% in the estimates of shower energies. Obviously, it is necessary to clarify the reason behind the observed difference in the estimates of energy that rely on calculated signals in ground-based detectors and on the results of their calibration by the fluorescence method. We note that the maximum energy $E_{\max}$ of the observed extensive air shower is a quantitative characteristic of processes of cosmic-ray acceleration [14] or a lower bound on the mass of hypothetic superheavy particles in the case of the top–down scenario [15].

In this article, we present the results obtained at the Yakutsk array for the energy spectrum within experimental procedures and their counterparts calculated by the method used at the AGASA array [11]. In the energy region $(1-2)\times10^{20}$ eV, we quote results for the spectrum that were deduced on the basis of a new, original, method [16] for estimating shower energies by using the CORSIKA [17] and GEANT4 [18] packages. This new method, which is based on calculations, was proposed for taking into account various unknown factors and fluctuations. For example, the nature (atomic number A) and energy E of the primary-cosmic-ray particle generating extensive air showers is unknown; the parameters that characterize the interaction of this particle with nuclei of air atoms in the region of ultrahigh energies (interaction model) are not known either. Moreover, extensive air showers generated by similar particles of the same energy are characterized, because of fluctuations in the longitudinal and transverse development of the showers, by different lateral distributions of shower secondary particles that reached the observation level. In order to interpret signals from each observed shower, it is therefore necessary to have a set of signals calculated within various models and induced by several tens of individual showers generated by various particles of various energies. Comparing signals for such a set of simulated showers with data for one observed extensive air shower in terms of the χ^2-minimization criterion, one can obtain the best estimates of the energy E and type of primary-cosmic-radiation particle, take most adequately into account the development of the observed shower in the atmosphere, and pinpoint the parameters of the interaction model. In this article, we also present the results of our analysis of the energy spectra obtained at various arrays for particles of primary cosmic rays. We propose an interpretation of the energy spectrum in question, assuming the existence of nonstationary individual sources of primary-cosmic-radiation particles in the region of ultrahigh energies, and conclude that data on the observation of six showers in the energy range $(2-3)\times10^{20}$ eV at various arrays do not confirm the GZK effect–induced decrease in the particle flux [9, 10].

2. ESTIMATES OF SHOWER ENERGIES

Experimental procedures are used at the Yakutsk array to estimate shower energies [13]. The signal $s(600)$ defined as the energy deposited in a scintillation detector at the distance of 600 m from the shower axis is the main parameter underlying the estimation of the EAS energy E. The energy E itself (in eV units) is determined by formula (1). At the AGASA array, the energies E are estimated on the basis of similar experimental procedures, but, at the last stage, the coefficients a and b in expression (1) are determined from calculations. Obviously, the same method for estimating energies is of great interest for the Yakutsk array as well, since it would make it possible to compare the results of calibration of the signal $s(600)$ by Cherenkov light with respective calculated values. By means of calculations, we have obtained the value of $a = 3 \times 10^{17}$ [19]. The estimate derived for the vertical-shower energy with this value of the coefficient a is smaller than the experimental value by a factor of about 1.6. Clearly, the energy spectra obtained by the two methods in question will be strongly different. Other alternative methods that would make it possible to estimate shower energies with allowance for an individual development of each shower in the region of ultrahigh energies are also of interest. In order to estimate the shower energies E, we propose employing a new, original, method [16] that relies on evaluating matrices of signals in scintillation detectors for a large set of simulated showers. This set is used to interpret one observed event. It is obvious that, for the entire set of observed extensive air showers, it is necessary to calculate many sets. In order to reduce the volume of computations, we can restrict ourselves at the first stage to applying the new method to the bin of highest energies. The development of individual showers in the atmosphere with allowance for the geomagnetic field was calculated by means of the CORSIKA-6.616 package [17] within the QGSJET2 [20] and GHEISHA 2002 [21] models at the weight parameter set to $\epsilon = 10^{-8}$ (thinning option). In order to calculate signals in ground-based scintillation detectors from various shower particles, we employed the GEANT4 package [18]. In the calculations, a ground-based scintillation detector was represented by the following model. There was an upper iron layer 0.1 mm thick; it covered a wood layer 15 mm thick followed by an aluminum layer 2 mm thick and a scintillator layer 50 mm thick. First, the database of scintillation-detector responses was calculated by means of the GEANT4 package. Signals generated by electrons, positrons, and photons of energy in the range 0.001–10 GeV and by muons of energy in the range 0.3–1000 GeV were calculated. All particles hit the detector at various zenith angles (in the range 0°–60°). Figure 1 shows

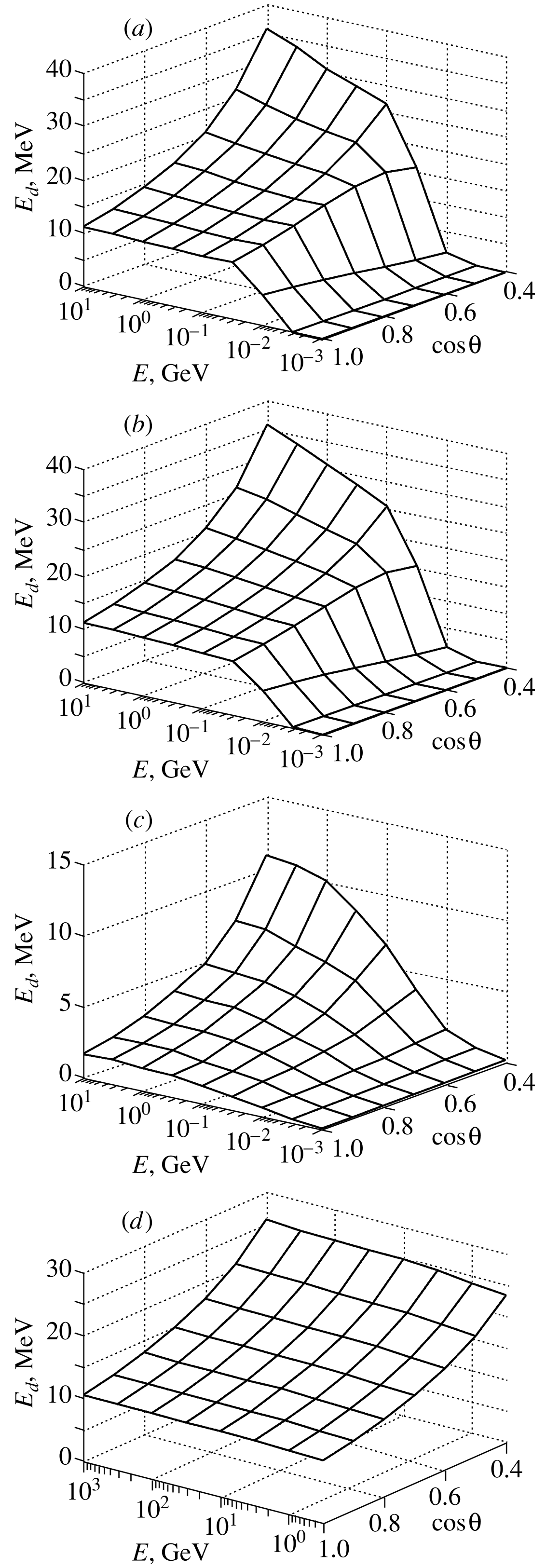

Fig. 1. Results of calculations for signals in a scintillation detector from (*a*) electrons, (*b*) positrons, (*c*) photons, and (*d*) muons.

the results of the calculations for (a) electrons, (b) positrons, (c) photons, and (d) muons. In those panels, the particle energy and the cosine of the angle of particle incidence to the detector are plotted along the two horizontal axes. The energy deposited in the detector is plotted along the vertical axis. One can see that the signal in the detector becomes stronger with increasing particle energy and angle of particle incidence.

This database of responses was used to calculate the response of a detector hit by a shower particle. An area of size 5×5 km^2 in the detector plane was broken down into 201×201 squares with a side length of 25 m. The CORSIKA-6.616 package [17] made it possible to calculate, for each individual shower in the detector plane, files containing parameters of particles that reached the observation level, while the database of responses permitted determining signals in each of the squares, which were treated as detectors. Thus, a 201×201 matrix of signals was calculated for each individual shower. In order to interpret data for each observed shower, we calculated several hundred such matrices of signals and compared them with data obtained with the aid of the χ^2-minimization criterion. An advantage of the new method is that it enables us to take into account most adequately fluctuations in the longitudinal and transverse development of extensive air showers and to estimate correctly the energy and nature of the primary-cosmic-radiation particle that generated extensive air showers and the parameters of the hadron-interaction model in the region of ultrahigh energies. In particular, the application of this method to the most powerful extensive air shower observed at the Yakutsk array made it possible to estimate the energy at $E \approx 2 \times 10^{20}$ eV for primary protons and at $E \approx 1.7 \times 10^{20}$ eV for primary iron nuclei [16].

3. ANALYSIS OF SPECTRA

The spectra of primary-cosmic-radiation particles was analyzed in the following way. For the shower energy, we will also use the notation $y = \log(E/1\text{ eV})$ in addition to E (in eV units). In three energy ranges $17.0 < y < 18.65$, $18.65 < y < 19.75$, and $19.75 < y < 20.01$, the energy spectrum was approximated in [8] by the power-law functions $J_i(E)$ $(i = 1, 2, 3)$:

$$J_1(E) = AE^{-3.25}, \quad J_2(E) = CE^{-2.81}, \quad J_3(E) = DE^{-5.1},$$

respectively. The constant A is $A \approx 7.1 \times 10^{28}$ m^{-2} s^{-1} sr^{-1} eV$^{2.25}$, while constants C and D are expressed in terms of A and the relations determining the equality of the values of the functions $J_i(E)$ at the boundary points $y_1 = 18.65$ and $y_2 = 19.75$. In order to compare the results of different experiments in the region of ultrahigh energies (above 10^{17} eV), we have chosen a universal spectrum $J_b(E) = AE^{-3.25}$ with the above value of the constant A. All possible special features of energy spectra will be considered with respect to this universal spectrum. In addition, we specify a reference spectrum $J_r(E)$ also obtained on the basis of HiRes data [8], with respect to which we will consider data of various experiments in the following way. We will use the approximations $J_r(E) = J_i(E)$ $(i = 1, 2, 3)$ in the energy range $17 < y < 20.01$ and, in contrast to what was done in [8], the approximation $J_r(E) = J_4(E) = J_1(E) = AE^{-3.25}$ in the energy region $y > 20.01$. The boundary point $y_3 = 20.01$ is determined by the intersection of the spectra $J_b(E)$ and $J_3(E)$. For the spectrum $J_r(E)$, we choose the representation

$$\log z_i = \log(J_i(E)/J_1(E)),$$

where the index i runs through the values from 1 to 4. In this representation, the spectrum $J_r(E)$ has the form

$$\log z_1 = 0, \quad \log z_2 = 0.44(y - 18.65),$$
$$\log z_3 = 0.484 - 1.85(y - 19.75), \quad \log z_4 = 0$$

in the four intervals, respectively. The values of $J(E)$ that were obtained at various arrays will be represented in the form

$$\log z = \log(J(E)/J_1(E))$$

against the background of the spectrum $\log z_i$.

4. RESULTS OF AN ANALYSIS OF SPECTRA OF PRIMARY-COSMIC-RADIATION PARTICLES

Obviously, the entire set of data obtained worldwide calls for an explanation. Of course, experimental errors exist, and one can assume that these errors are large in some cases. However, there is no explanation why showers of energy well above the threshold for the GZK effect are observed in some cases (see [11, 13]) but are not observed in others; also, the answer to the question of whether the particle flux does indeed decrease in the region of ultrahigh energies can be sought in the possible structure of the energy spectrum of primary-cosmic-radiation particles. Usually, this spectrum is assumed to be universal and stationary. These properties of the spectrum follow from the hypothesis of a uniform distribution of approximately identical sources in space [5]. Under the assumption of a power-law spectrum of proton production in these sources, the theory of cosmic-ray propagation in an intergalactic medium [5] explains well the observed spectrum, including the “dip” (an

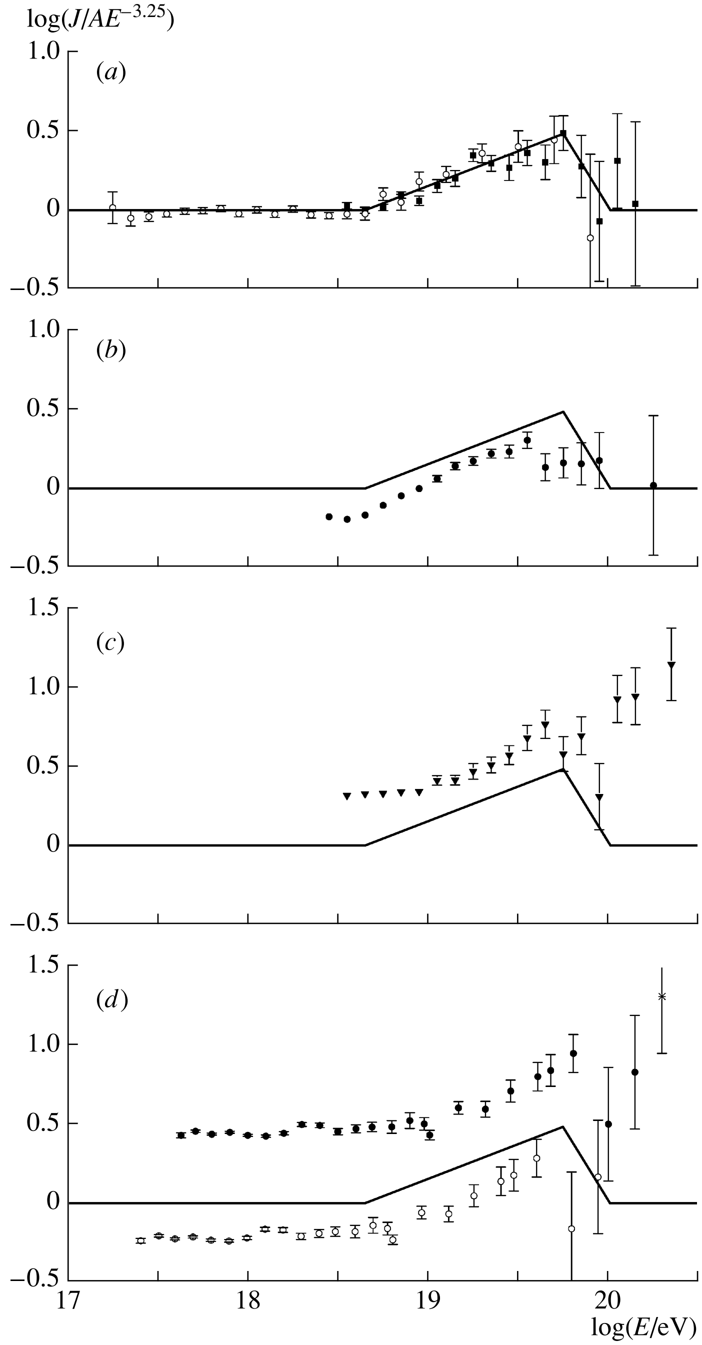

Fig. 2. Results of representing in the form $\log z = \log(J(E)/J_1(E))$ spectra obtained at various facilities: (a) HiRes data [8] [(open circles) HiRes2 and (closed boxes) HiRes1], (b) data of the Pierre Auger Observatory (PAO) [7] (closed circles), (c) AGASA data [11] (closed inverted triangles), and (d) data from Yakutsk array [13] {(closed circles) experimental spectrum, (open circles) spectrum calculated for the Yakutsk array by the method used at the AGASA array [11], and (asterisks) estimate of the spectrum for a bin in the region of maximum energies on the basis of the original method proposed in [16]}. The solid curve represents the universal spectrum $J_r(E)$.

increase in the steepness of the spectrum because of the production of electron–positron pairs at energies above 10^{18} eV) and a bump in the energy range $(4.5-5.75) \times 10^{19}$ eV. However, it would be natural to assume that, in addition to uniformly distributed sources, there are also relatively powerful cosmic-ray sources whose distribution may be random. The closest of such sources can make a nonstationary contribution to various relatively narrow intervals of the spectrum in the region of extremely high energies.

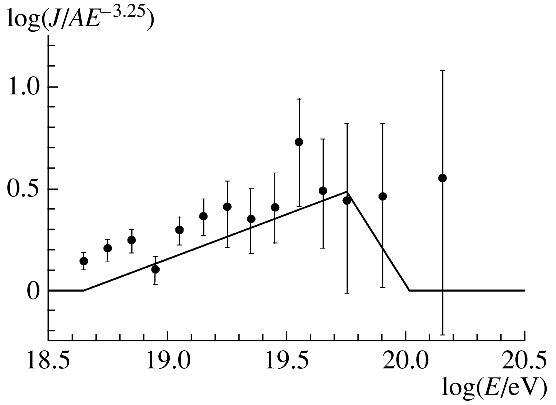

Fig. 3. Preliminary spectrum obtained at the TA array [27] (points with error bars) according to data from scintillation detectors and upon reducing the energy by a factor of 1.4. The solid line represents the reference spectrum $J_r(E)$.

If one does not require a high power of the sources, their contribution may change significantly with time. We propose considering the excess of particles from such sources against the background of a universal spectrum for which we take $J_b(E)$. We also propose contrasting the decrease in the particle flux because of the GZK effect against this spectrum rather than against the bump as was done previously in [7, 8]. Obviously, this is a more challenging task. However, these assumptions make it possible to avoid obvious contradictions.

In the representation chosen above, the experimental spectra $\log z = \log(J(E)/J_1(E))$ obtained at different arrays are displayed in Fig. 2. As might have been expected, HiRes data from [8] are in excellent agreement with the reference spectrum, data of the Pierre Auger Observatory (PAO) [7] lie lower than it, and AGASA [11] and Yakutsk [13] data lie higher. We will now consider special features of the spectrum in Fig. 2 that catch the eye. First, data from [8] (and, indirectly, data from other arrays) show that, in the energy range 2×10^{17}–4.5×10^{18} eV, the slope of the spectrum remains unchanged. This result is of paramount importance for the theories of origin of cosmic rays and for searches for the boundary of the transition from galactic to extragalactic cosmic rays. Second, data from all arrays show that, in the energy range $(4.5–5.75) \times 10^{19}$ eV, there is an excess of primary-cosmic-radiation particles. It is not mandatory to treat this particle excess as a contribution of extragalactic sources, which decreases in the region of ultrahigh energies because of the GZK effect or as the result of the production of electron–positron pairs [5]. It is admissible to treat it as a direct contribution of individual sources. In this case, not only protons but also heavier nuclei could be primary particles. In order to clarify the nature of the excess in question, it is therefore very important to study the particle content of primary cosmic rays in this energy region. The intensity I of such individual sources in the region of ultrahigh energies can be determined as an integral of the differences $J_2 - J_1$ and $J_3 - J_1$. Estimations yield $I \sim 4 \times 10^{-14}$ m^{-2} s^{-1} cp^{-1}. If a value of $R \sim 30$ Mpc is taken for the distance to the sources at a typical energy of $E = 4 \times 10^{19}$ eV and a particle emission angle of about 1 sr, then the power of these sources is estimated at about 10^{34} W, which is consistent with our previous estimates in [22] and [23]. In the representation chosen here, it is much more difficult to notice a sharp decrease in the particle flux at energies above 10^{20} eV (GZK effect). Indeed, the results presented in [8] indicate that the number of events with an energy in excess of 6.3×10^{19} eV that is expected on the basis of the spectrum $J_2(E)$ is 43.2, while the number of observed events is 13. In our representation, the number of events that is expected in accordance with the universal spectrum $J_r(E)$ is 16. With allowance for Poisson fluctuations, this number agrees with the observed one. According to [7], the numbers of expected events with energies above 4×10^{19} eV and with energies above 10^{20} eV are 167 ± 3 and 35 ± 1, respectively, while the observed numbers are 69 and 1. According to the universal spectrum $J_r(E)$, the numbers of expected events are 137 and 7, respectively. In that case, the discrepancy decreased but it remained. This decrease can be considered as the observation of the GZK effect with respect to the basic spectrum $J_b(E)$, but different reasons can also be sought. It should be borne in mind that the intensity of the reference spectrum with respect to which the number of expected events was estimated is higher than the intensity of the spectrum in [7] by a factor of about 1.5. It should also be emphasized that, in the region where the GZK effect is manifested, the shower energy was estimated in [8] by means of cutting the spectra of signals with intensity isolines [24]. We believe that because of large fluctuations, this may lead to sizable systematic errors in estimating energies for a small number of events [16] in the region of extremely high energies.

We note that the intensity of the spectrum obtained at the Yakutsk array from the calculation by the method used at the AGASA array (open circles in Fig. 2d) lies lower than the experimental spectrum (closed circles) by a factor of about five. This discrepancy may be due to both model uncertainties and experimental errors, especially because of the use of the method developed in [24]. Finally, we indicate that, according to the original method for estimating energies, the existence of showers in the energy range $(1–3) \times 10^{20}$ eV is possible (asterisk in Fig. 2d). It

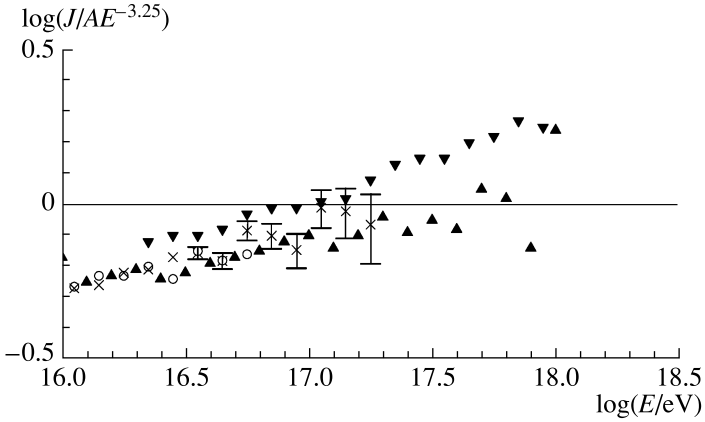

Fig. 4. Data on the spectrum from the experiments reported in (circles) [29], (crosses) [30], and [closed triangles if the numbers of charged particles and muons were used in constructing the spectrum and inverted closed triangles if the parameter $s(500)$ was used] [31]. The solid line represents the reference spectrum $J_r(E)$.

is noteworthy that this asterisk is nearly coincident with the rightmost point obtained at the AGASA array (see Fig. 2*c*), where eleven showers in this energy region and four showers at energies in excess of 2×10^{20} eV were observed [11]. Hypothetically, these showers could be generated by nonstationary individual sources. Possibly, this energy region is dominated by heavy nuclei. Also, we cannot rule out the possibility that, in the energy range $(1-3) \times 10^{20}$ eV, there is no GZK effect—induced decrease in the flux of primary-cosmic-radiation particles. It should be noted that extensive air showers of energy 3.2×10^{20} eV [25] and 2×10^{20} eV [26] were observed by the fluorescence method at the Fly's Eye array and Pierre Auger Observatory. These observations are of paramount importance. Preliminary small-statistics data from the TA array [27] are also compatible with our hypothesis. Figure 3 shows preliminary data for the spectrum obtained on the basis of readings of ground-based scintillation detectors (points with error bars). The estimates obtained for the energy on the basis of these readings were reduced by a factor of 1.4 [27] in order to match them with respective estimates by fluorescence light. The solid line represents the spectrum $J_r(E)$. We note that the last point in this spectrum and the point in Fig. 2*d* (closed circle) are nearly coincident. If we do not reduce the energy by a factor of 1.4, the last point in Fig. 3 is nearly coincident with the asterisk in Fig. 2*d*. This is indicative of the consistency of data from the TA and Yakutsk arrays. We also note that, in Figs. 2*c*, 2*d*, and 3, one cannot see a decrease in the flux of primary-cosmic-radiation particles at energies above 10^{20} eV. If the GZK effect is not observed upon the enlargement of statistics and if primary cosmic radiation is dominated by protons, then it will be a chance to admit Lorenz invariance violation [28]. In order to determine the region of a possible transition from galactic to extragalactic cosmic rays, we can depict data for the spectrum in the energy range $10^{16}-10^{18}$ eV in the same representation as in Fig. 2. Figure 4 shows data of the experiments reported in [29–31]. From Fig. 4, one can see that, in this energy range, the exponent of the spectrum is smaller than the exponent of the reference spectrum by 0.1 to 0.15, but, in the energy range $10^{17}-10^{18}$ eV, data from [30] and [31] (triangles) are in accord with the reference spectrum. The other part of the data from [31] (inverted triangles) lie substantially higher, which can be explained by the use of the method from [24] in constructing the spectrum. Obviously, the transition from a spectrum with an exponent of 3.15 to a spectrum with an exponent of about 3.25 may occur at energies in the range $(1-2)\times10^{17}$ eV, but it is clear that additional experiments are required for refining the spectrum and particle content in this energy region.

5. CONCLUSIONS

We have considered different methods for constructing the energy spectrum on the basis of data obtained at the Yakutsk array. In addition to the standard method based on experimental procedures, we have applied a method similar to that used at the AGASA array. Moreover, we have employed a new, original, method for estimating energy in the region of its extremely high values. In order to compare spectra obtained at different arrays, we have proposed making use of the basic spectrum $J_b(E) = AE^{-3.25}$. We have shown that the energy spectra obtained at different arrays do not comply with one another. There is a glaring contradiction between the spectra obtained by using the fluorescence method for estimating energy and by using signals calculated for scintillation detectors. The conclusion that the flux of primary-cosmic-radiation particles decreases because of the GZK effect [7, 8] has not yet been confirmed by data from [11, 13] and [25–27]. We have speculated on the possible role of individual sources, which could make a nonstationary contribution to various regions of the spectrum of primary-cosmic-radiation particles.

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