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Cosmic particles with energies above 10^{19} eV: a brief summary of results

S V Troitsky

1. Introduction

Ultra-high-energy (above 10^{19} eV) cosmic rays (UHECRs) have continued to attract the interest of researchers in both particle physics and astrophysics for decades. Questions arising in this field have been related to the origin of particles with these high energies, which do not appear in the Universe under any other conditions, and to searches for new physics, which may reveal itself in this energy range and result in deviations of experimental results from theoretical expectations. As we see below, these two groups of questions remain topical and, to a large extent, determine the present development of research in the overlap of particle physics and astrophysics.

Studies of UHECR physics are restricted by two principal complications related to specific properties of the phenomena under investigation. First, the flux of these particles is very low (on average, only one particle with the energy we are considering arrives at one square kilometer per year). Hence, direct registration of primary particles, which interact in the upper layers of the atmosphere, with the help of flying detectors is impossible, and we have to study them indirectly with ground-based installations capable of detecting extended atmospheric showers (EASs) caused by these particles. Moreover, even large ground-based detectors working for many years collect the number of events that is negligible compared, for instance, with the number of astrophysical photons detected by a telescope in any other energy range. Second, the interaction of the particles with the atmosphere occurs at energies far beyond the laboratory reach (for a 10^{19} eV proton interacting with an atmospheric nucleon at rest, the center-of-mass energy is hundreds of TeV); therefore, the models that relate the EAS development to properties of the primary particle inevitably include extrapolation of the interaction properties into yet unexplored domains of energy (and momentum transfer).

The experimental installations in operation at present may be divided based on the techniques they use into ground arrays of surface detectors (SDs) and fluorescent telescope detectors (FDs). SDs detect particles from an EAS at the surface level. Detectors form an array with a spacing of ~ 1 km and are capable of determining the lateral distribution function (LDF) of the particle density in a shower. An FD is a telescope that detects ultraviolet emission caused by fluorescence of atmospheric nitrogen molecules excited by charged particles of the shower. An SD registers a two-dimensional slice of an EAS only, but it works independently

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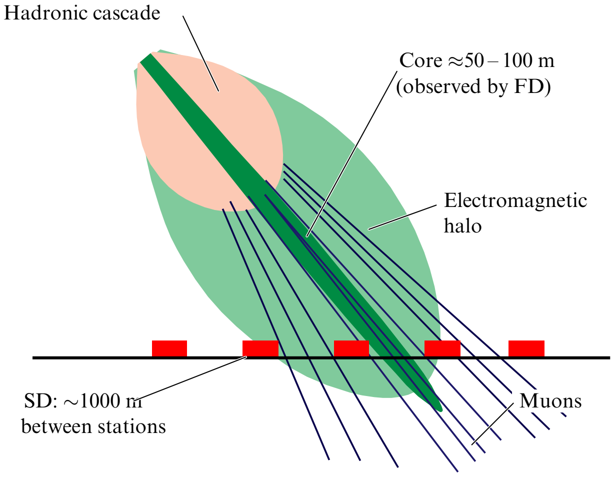

Figure 1. Sketch of an EAS development and detection.

of the weather conditions and time of day and is able to detect various shower components (electromagnetic, muon, and baryon). An FD sees the longitudinal development of a shower, but is able to register events on clear moonless nights only (roughly, this constitutes about 10% of the time) and is sensitive to the electron component only. At the same time, an SD mostly detects the peripheral part of the shower, while the FD sees the central core (see Fig. 1).

Presently, three experiments in the world are capable of studying EASs caused by primary particles with energies above 10^{19} eV. They are very different from each other and have different advantages and disadvantages.

The Yakutsk complex EAS array has already been in operation for more than 40 years and, presently, has SDs plastic scintillators covering about 10 km^2, moderate by modern standards. Its principal advantage is the possibility of simultaneous detection of various EAS components. It is the only modern installation that provides large-exposure data of muon detectors; these results are extremely useful both in the analysis of primary chemical composition and in testing models of high-energy particle interactions.

The Telescope Array (TA) experiment, located in the USA (state of Utah), is operated by an international collaboration, which includes Russian scientists, and combines an SD of plastic scintillators with the array area $\sim$ 680 km^2 and three FD stations. An important advantage of this installation is the possibility of the hybrid regime, that is, of simultaneous detection of the same EAS by both SDs and FDs with independent reconstructions (for FDs, this can be done in stereo).

The largest modern UHECR experiment, the international *Pierre Auger Observatory* (PAO) in Argentina, has the SD array area $\sim$ 3000 km^2, which makes it a clear leader in the exposure, and four FD stations. The observatory is also capable of hybrid detection; however, reconstruction using FDs is always dependent on the SD and, notably, stereo data are not available. One might doubt whether the choice of water tanks for the SD was perfect: these detector stations are hypersensitive to the muon EAS component, the one which is the least understood in EAS models; this sometimes results in increased systematic uncertainties.

Together with past experiments that have already finished their work, these ones sometimes obtain results that are not in full mutual agreement. Notably, in 2012, working groups were created including representatives of all three currently operating experiments. The first results of the work of these groups were discussed at a conference at CERN last spring; the discussion in Section 3 is partly based on them.

2. Principal observables

In this section, the principal UHECR observables are defined, those related both to an individual EAS and to the ensemble of data. This information is used in the next section, where experimental results are discussed. Independently of the EAS detection method, the processing of raw data allows extracting information on a few basic parameters of the primary particle, namely its type, energy, and arrival direction.

Arrival direction. The least model-dependent observable reconstructed from an EAS is the arrival direction of the primary particle, whose determination is purely geometrical. SD reconstructs the arrival direction from the trigger time of individual detector stations to which the shower front, moving almost at the speed of light, arrives nonsimultaneously. The FD is able to directly fix the position of the plane containing the shower core and the detector position; the core position is given in stereo by the intersection of two such planes; in observations by only one telescope, it is necessary to take the temporal development of the signal into account. The precision of the SD geometric reconstruction depends on the number of triggered stations, in addition to the precision of time measurements; in the FD case, the key parameter is the distance between the telescope and the shower core. In practice, the precision with which the arrival direction is determined decreases as the effective area of the detector increases: SD stations are positioned at a larger spacing and FD telescopes observe a larger volume in the atmosphere. The best-ever angular resolution (68% of events reconstructed with a precision of no worse than 0.6°) was achieved in a previous-generation experiment, HiRes, which operated two FD stations in stereo. For present-day experiments with a large effective area, this quantity is $\sim 1.5°$.

Energy. The primary energy is reconstructed indirectly. In the SD case, the signal is recorded at each particular detector station, and then the lateral distribution of the signal is compared to the expected one. This procedure of energy determination introduces a considerable uncertainty related to the modeling of the expected signal for various energies. FDs observe the shower core, which carries the dominant part of the energy; this method allows estimating the total energy of electrons and positrons in the core on the basis of measurements and is therefore often called calorimetric. We note, however, that significant sources of uncertainty remain, related both to the value of the fluorescent yield and to the estimate of the energy not carried by the core electrons. In all cases, an additional source of (statistical) uncertainty is related to fluctuations in the first interactions of particles in the atmosphere. Presently, the energy of a particular primary particle is estimated with a $\approx (15-20)\%$ statistical error and with a $\approx 25\%$ systematic uncertainty.

Type of the primary particle. Due to both considerable fluctuations in the development of EASs initiated by similar primaries and similarities in showers initiated by different primaries, it is presently hardly possible to determine the type of the original particle for a particular event. Approaches to this issue are based on the study of particular EAS components (electromagnetic, muon, hadron, Cherenkov, etc.) and of the detailed properties of longitudinal and/or lateral shower development (depth of the maximal development, front shape, etc.). Even probabilistic estimates that result from the use of these methods are strongly model dependent.

Observables of an ensemble of EASs. Three principal observables determined for each event allow analyzing the ensemble of showers and obtaining statistical information about the UHECR properties: the primary composition, the energy spectrum, and the distribution of arrival directions. For the last one, searches are made for deviations from an isotropic distribution at either large (global anisotropy) or small (clustering; correlation with potential sources) angular scales. Results of these studies are discussed in Section 3.

3. Review of experimental results

3.1 Energy estimation and spectrum

The UHECR energy spectra measured by various experiments are given in Fig. 2a. Determination of the spectrum, which is based on the absolute measurements of the primary-particle energy and, for FDs, also on detailed simulation of the exposure, cannot be model-independent. In order to suppress both the arbitrariness related to the choice of the model and the systematic errors, it has been suggested [1] that the reason for the difference of the spectra reconstructed by various experiments is the energy-independent systematic error of the energy measurement. Indirectly, this suggestion is supported by the systematic difference between FD and SD energies for primary particles of EASs reconstructed by the two methods simultaneously, both in PAO and in TA. The amount of the related systematic shifts is easy to find by requiring that the spectra measured by different experiments coincide. To determine the absolute normalization, we need an additional theoretical assumption; in Ref. [1], the energy scale is calibrated by the theoretically predicted position of a spectral dip related to the proton energy losses by production of electron–positron pairs. In a wide energy interval $10^{17.5} \lesssim E \lesssim 10^{19.5}$ eV, both the shape and the normalization of the shifted spectra coincide; this fact strongly supports the approach. However, we can see from Fig. 2b that this agreement is slightly worse at the highest energies.

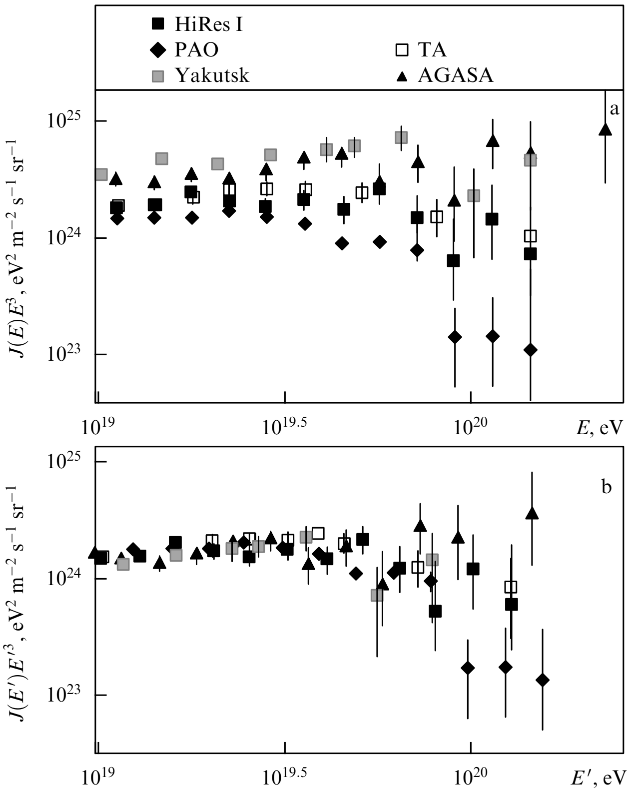

Figure 2. The UHECR spectra (the particle flux $J(E)$) measured by the AGASA [2], Yakutsk [3], HiRes I [4], PAO [5] and TA [6] experiments, (a) before and (b) after the energy-scale shifts. The respective energy shifts are $E'/E = 0.652, 0.561, 0.911, 1.102$, and 0.906 [7].

For a long time, the interest in UHECR physics was heated by the predictions by Greizen [8] and Zatsepin and Kuzmin [9] of a cutoff expected in the spectrum of cosmic-ray protons at energies above $\sim 7 \times 10^{19}$ eV, which corresponds to the pion production threshold in proton interactions with photons of the cosmic microwave background (CMB) radiation (the GZK effect), and, at the same time, by experimental observation of EASs initiated by particles whose reconstructed energies exceeded 10^{20} eV (the first of these events had been detected by the Volcano Ranch experiment [10] even before the CMB was discovered). As we can see from Fig. 2, the existence of these events has been confirmed by all experiments; however, the latest data indicate the presence of spectral suppression [4, 6, 11]. The statistical significance of the suppression is usually estimated by a comparison of data with the continuation of a power-like spectrum, which is excluded at a certain confidence level. Clearly, the quantitative estimates of significance depend on the model of the spectrum continuation; therefore, we do not quote the numbers here. It should also be kept in mind that these results do not prove that the suppression is related to the GZK effect, nor do they exclude a step-like continuation of the spectrum.

3.2 Primary composition

Presently, the question about the UHECR primary composition is open. For the last few years, contradictory results of HiRes and PAO have been under active discussion, both at conferences and in the literature. While the results of the former experiment are in full agreement with the energy-independent, mostly proton, composition, measurements by the latter indicate a gradual change toward heavier primary nuclei as the energy increases. Both analyses used, as the principal observable, the depth $X_{\max}$ of the maximal shower development, as determined by FDs, and the amount of its fluctuations. Besides these two experiments, $X_{\max}$ has been studied, with smaller statistics, with the FD data at TA and with the Cherenkov-light data in Yakutsk (in the latter case, the fluctuations have also been estimated).

The results of all experiments located in the northern hemisphere (and therefore observing the northern sky) agree with the proton composition, contrary to the PAO (Southern hemisphere) results. This disagreement might be explained by the presence of nearby sources, resulting in a significant dependence of the primary composition on the direction on the celestial sphere. However, in 2012, the PAO collaboration presented a separate analysis of events (see Ref. [12]) derived from the southern and northern celestial hemispheres (the equatorial part can be observed by all experiments); no signs of a systematic difference were found. The northern experiments to date have not yet collected the number of events sufficient for this kind of analysis.

Another possible explanation for the contradiction in $X_{\max}$ results is the difference in methodologies of the data processing by PAO and Yakutsk versus HiRes and TA. While the value of $X_{\max}$ of an individual shower is defined in a similar way by all groups, the study of an ensemble of showers proceeds differently: the first pair of experiments, by means of imposing numerous cuts that significantly reduce the number of events, select the most representative, minimum-bias sample in which the $X_{\max}$ distribution should coincide with that of all EASs, both detected and missed in the sample. In the second pair of experiments, on the contrary, the full set of detected EASs is considered, but selection effects are taken into account in calculating the theoretically expected values $X'_{\max}$ for a given particular sample. To add to the complication, HiRes used a slightly different quantity than those in PAO and Yakutsk to parameterize fluctuations. The direct comparison of the results obtained by various experiments is therefore possible only in terms of the final result, the primary nuclear composition, which is traditionally parameterized by the mean logarithm of their atomic mass, $\langle \ln A \rangle$. Unfortunately this analysis inevitably depends on the shower-development model that is used to relate observable parameters to $\langle \ln A \rangle$.

The results of this comparative analysis, with the EAS parameters mentioned above as well as some others, are presented in Fig. 3, where we used QGSJET II [13] as a model of high-energy hadronic interactions (this choice was determined by the availability of published data for comparison with this model).

In our opinion, the scatter of the values of $\langle \ln A \rangle$ obtained by means of various methods indicates that it may be too early to claim any significant contradiction between experiments. In particular, once expressed in terms of $\langle \ln A \rangle$, the difference in the $X_{\max}$ results between the HiRes and PAO analyses does not exceed the difference between PAO $X_{\max}$ and fluctuation results. Probably, systematic errors still dominate over real effects in the studies of the primary composition.

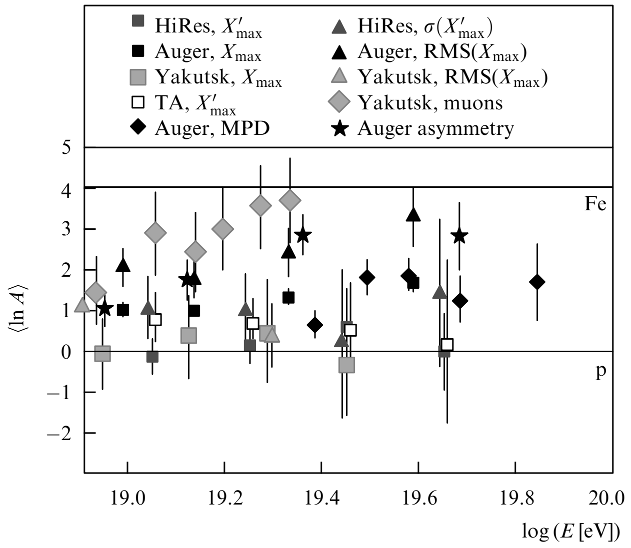

Figure 3. Results of the analyses of the UHECR primary composition by various methods: the maximal shower development depth and its fluctuations from the data of the HiRes [14], PAO [15], TA [16], and Yakutsk [17] experiments; Yakutsk muon data [18]; reconstructed muon production depth ('MPD') and shower front shape asymmetry ('asymmetry') from the PAO SD data [19].

To conclude the discussion of the chemical composition, we note that, astrophysically, a significant number of primary heavy nuclei look less probable than the (predominantly) proton composition because numerous nuclei require additional mechanisms of increasing metallicity in the injected matter by several orders of magnitude with respect to the maximal known stellar metallicity. The argument that particles with larger electric charges are accelerated more efficiently leads to the requirement of a sharp jump (not observed experimentally) in both the composition and the total flux of cosmic particles at energies that correspond to the maximal energy of accelerated protons.

3.3 Anisotropy of the arrival directions

The small number of events, relatively poor angular resolution, and deflections of charged particles by cosmic magnetic fields make it impossible, presently, to identify UHECR sources object by object, as is customary in classical astronomy. Instead, one has to operate by statistical methods and to search for manifestations of particular models of the population of sources in an anisotropic distribution of cosmic-ray arrival directions for the entire sample. The searches for global and small-scale anisotropy can be singled out.

The global anisotropy of arrival directions is expected when the observed cosmic-ray flux is due to a limited number of more or less nearby sources. This picture is relevant in two cases: (i) there is a significant overdensity of sources close to the observer and (ii) particles from distant sources do not reach us for some reason. The first case corresponds to sources in our Galaxy. The second option is relevant for astrophysical sources of protons with sub-GZK energies; the dominant contribution to the cosmic-ray flux at these energies should come from sources inside the so-called GZK sphere with a radius of the order of 100 Mpc. Since the matter inside this sphere is distributed inhomogeneously, the astrophysical scenario with a large number of proton sources implies an anisotropic distribution of the arrival directions. This distribution can be predicted from a model of the distribution of sources, that is, of matter in the Universe, supplemented by some assumptions about particle propagation. On the other hand, searches for manifestations of some particular classes of sources in *small-scale anisotropy* basically amount to studies of the autocorrelation function (clustering) or of correlations of cosmic-ray arrival directions with positions of objects of a certain class.

Results of most analyses of the distribution of arrival directions of primary particles with energies above 10^{19} eV are in statistical agreement with the isotropic distribution at a good confidence level. At the same time, in some particular cases, there are indications of deviations from isotropy: the data, being compatible with an isotropic distribution, do not exclude some anisotropy scenarios. For instance, in the southern hemisphere (PAO), the global distribution of the arrival directions suggests their possible correlation with the large-scale structure of the Universe, while this is not seen in the data of northern experiments (see Fig. 4); TA results exclude this correlation at the 90% confidence level for events with energies $E > 10^{19}$ eV (for $E > 4 \times 10^{19}$ eV, arrival directions are consistent with both scenarios).

One of the most important recent results for astrophysics is the lack of statistically significant clustering of arrival directions at small scales. The search for clusters of events allows constraining the number of their sources in the nearby

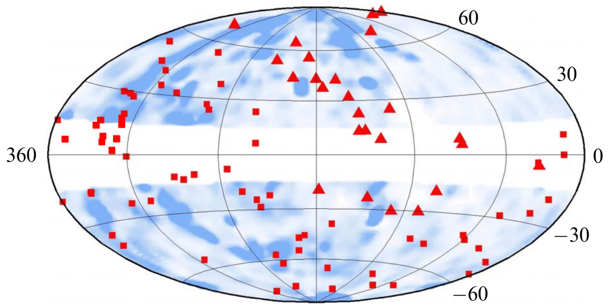

Figure 4. The expected flux of protons with energies $E \gtrsim 5.5 \times 10^{19}$ eV from extragalactic sources, whose distribution follows the large-scale structure of the Universe, with the exposures of PAO and TA taken into account (galactic coordinates; darker regions correspond to higher flux; the method of calculation is described in Ref. [20]; relative exposures are normalized to the number of events; the white strip corresponds to the zone of galactic absorption where precise data on the structure are missing), together with the arrival directions of PAO [21] (squares) and TA [22] (triangles) events.

Universe: in the limit where there is only one source, the arrival directions would all concentrate in a single spot around it; on the contrary, for infinitely many sources, the distribution would be isotropic. A quantitative method that results in a lower limit on the number of sources from the lack of clustering was developed in Ref. [23]; its somewhat more complicated version was recently applied to the PAO results [24]. Reliable constraints on the number density of sources can be obtained for the highest energies where the flux is dominated by nearby sources (because of the GZK effect), while particle deflections by magnetic fields are not large. The result of this analysis is the bound $n \gtrsim 10^{-4}$ Mpc^{-3} on the concentration of sources of particles with $E \gtrsim 5.5 \times 10^{19}$ eV (under the assumption of small deflections). It is a very restrictive bound: the sources should be much more abundant than it is assumed in most theoretical models. Indeed, simple bounds on the physical parameters of a source of particles with these energies [25] demonstrate that for classical mechanisms of diffusive acceleration (e.g., in shock waves), the required conditions are fulfilled only in very exotic and rare objects, the most powerful active galaxies. At the same time, a less popular mechanism of direct acceleration of particles in the magnetospheres of supermassive black holes [26] allows satisfying the concentration bounds and constructing a model of the population of sources [27].

The autocorrelation function for the arrival directions of events with $E > 10^{19}$ eV is fully consistent with that expected for an isotropic distribution [22]; but at higher energies, slight deviations from isotropy are observed that consist of excesses of events separated by an angular scale of about 15°. In the PAO data, this excess is determined by a spot of events [28, 29] around the nearby radio galaxy Cen A. This spot may also be responsible for the effect of the correlation with the large-scale structure, because Cen A is projected to a more distant but very large supercluster of galaxies. In the northern hemisphere (TA), no evident spot can be seen, but an excess in the autocorrelation function is present. We note that for $E > 10^{20}$ eV, the PAO and TA experiments have detected only six events, two of which coincide within the angular resolution [30].

One of the best-known results of comparison of particle arrival directions with positions of astrophysical objects of a certain class is the conclusion of the Pierre Auger collaboration [31] on the correlation of arrival directions of particles with $E > 5.6 \times 10^{19}$ eV with positions of nearby active galaxies, which has been interpreted as evidence that the events in this energy range are caused by protons either from these galaxies or from other objects distributed in the Universe in a similar way. This conjecture is hardly consistent with the analyses of other observables (including the chemical composition and the global anisotropy) and with the astrophysics of the sources. It has been confirmed by the Yakutsk data [32] and not confirmed by HiRes [33]. More recent PAO data [21] point to a much weaker effect than in Ref. [31]. The TA results [22] exclude the original estimate of the strength of the effect [31] and are consistent both with the total absence of the effect and with the estimate in [21].

4. Particle physics applications

Cosmic rays allowed discovering many elementary particles in the past, and the fundamental physics of particles and interactions currently continues to exploit information coming from cosmic-ray physics and astrophysics. The primary avenues here are to study hadronic interactions at energies an order of magnitude higher than those achieved in accelerators; to search for unknown effects that affect the atmospheric shower development; and to search for 'new physics' in order to solve problems with the standard explanation of astrophysical results.

4.1 Particle interactions at very high energies

The center-of-mass energy of a proton–proton collision at the Large Hadron Collider (LHC) is an order of magnitude less than that of the first interaction of a UHE particle in the atmosphere. On the one hand, this results in a large uncertainty in models describing EASs (although the LHC results, in particular those of the dedicated experiment LHCf, are presently in active use to improve the models, one cannot avoid extrapolation). On the other hand, measurement of model-independent EAS properties allows directly extracting quantitative information about the first interaction. Both aspects are illustrated by Fig. 5.

Today, the precision of both the models and the measurements is insufficient to make any statement about the influence of new physics on shower development.

4.2 New physics searches

We now discuss two examples (far from being unique but, in our opinion, currently very interesting) of the application of UHECR to searching for and constraining new physics — particles and interactions assumed in theories that extend the Standard Model (SM) of particle physics and attempt to solve some of its problems [41].

Neutral particles from BL Lac type objects. In 2004, the analysis of a data sample with the best ever angular resolution in UHECR physics (HiRes stereo [42]) revealed [43] statistically significant correlations of the arrival directions of a small fraction (about 2%) of cosmic particles with energies above 10^{19} eV with bright BL Lac type objects — powerful active galaxies of a certain class located far from Earth. The angular resolution of the experiment was much smaller than the value of the expected deflection of protons with these energies in the Galactic magnetic field, and therefore this observation pointed to the existence of UHE neutral particles that travel over cosmological distances. A subsequent publication by the HiRes collaboration [44] confirmed this

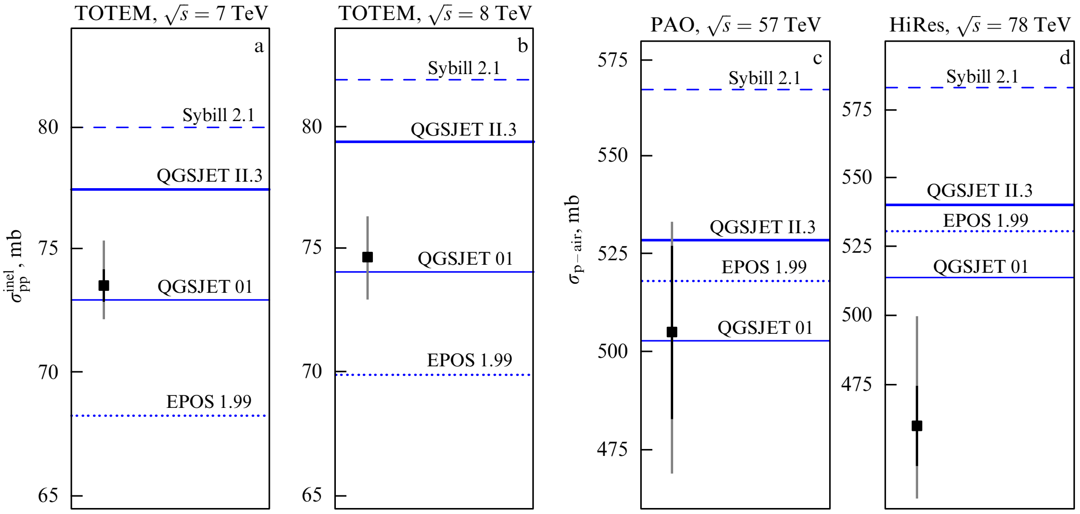

Figure 5. A comparison of cross sections used in the hadronic interaction models Sybill 2.1 [34], QGSJET 01 [35], QGSJET II [13], and EPOS 1.99 [36] (values taken from Ref. [39]) with the experimental results. Inelastic pp cross sections from the models and from the TOTEM experiment data at the LHC energy (a) $\sqrt{s} = 7$ TeV [37] and (b) $\sqrt{s} = 8$ TeV [38]; 'p–air' cross section from the models and from the EAS analysis data by the PAO [39], (c) $\sqrt{s} = 57$ TeV, and (d) HiRes [40], $\sqrt{s} = 78$ TeV, experiments. Statistical and systematic uncertainties are respectively shown in black and gray.

result with an alternative analysis method. This phenomenon cannot be explained in the frameworks of standard physics and astrophysics (see, e.g., the discussion in Ref. [45]). Popular extensions of the SM, e.g., supersymmetry, do not help, either. The only consistent explanation of this effect, which is also helpful in solving some other astrophysical problems and can be tested experimentally, has been proposed in Ref. [46] and is based on the phenomenon of axion–photon oscillations. Unfortunately, the effect itself has not yet been tested in a similar independent experiment: a worse angular resolution of the only installation (TA) that operates FDs in the stereo mode requires a very large number of events, not yet collected. The absence of the effect in the PAO SD data [47] agrees with the predictions of the axion–photon conjecture: PAO water tanks are almost insensitive to muon-poor EASs initiated by primary photons.

Superheavy dark matter. One of the experimental results whose explanation requires an extension of the SM is the presence in the Universe of a large amount of invisible matter, so-called dark matter. In a certain class of models, it is supposed that this matter consists of metastable (with lifetime τ_{X} of the order of the lifetime of the Universe), superheavy (mass $M_{\mathrm{X}} > 10^{20}$ eV) X particles, whose decay products may involve UHECR primary particles. The decay of the X particles can be described in a sufficiently model-independent way, because the key role in its physics is played by relatively well-understood hadronization processes. Among the predictions of this scenario are a very hard spectrum at the highest energies, a large fraction of primary photons, and Galactic anisotropy of the arrival directions. The most restrictive constraints on this scenario come presently from the bounds on the photon flux, but still leave open a significant part of the X-particle parameter space [48]. This model currently attracts some special interest because no candidate for the dark-matter particle was found at the LHC.

5. Conclusion

The UHECR physics has remained, for decades, one of the most interesting fields at the intersection of astrophysics and particle physics. Despite serious progress in experiments, we presently cannot say much about the origin of particles with energies above 10^{19} eV, and only a few models of particle acceleration in astrophysical sources can simultaneously satisfy both the constraints on physical conditions in these accelerators and the strict lower bound on the number density of sources obtained recently from the absence of clustering of arrival directions. The results of the studies of the chemical composition of primary particles in this energy range are probably dominated by systematic errors and not by real physical effects. The physical reason for the systematic difference in the primary energy determination by means of different methods is still unknown. Some indications of possible manifestations of new physics in cosmic rays deserve close attention.

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