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

S.V. Troitsky

Institute for Nuclear Research of the Russian Academy of Sciences,
60th October Anniversary Prospect 7A,
117312, Moscow, Russia

Abstract

Experimental results on ultra-high-energy cosmic rays are briefly reviewed and their interpretation is discussed. The results related to principal observables (arrival directions, energies and composition) of primary particles of extended air showers as well as particle-physics implications are addressed.

1 Introduction

Ultra-high-energy (above $10^{19}$ eV) cosmic rays (UHECRs) continue to attract interest of researchers working in both particle physics and astrophysics for decades. Questions arisen 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 as well as to searches of new physics which may reveal itself in this energy band and result in deviation of experimental results from theoretical expectations. As we will see below, these two groups of questions remain topical and, to a large extent, determine the present development of research at the border of particle physics and astrophysics.

Studies of UHECR physics are restricted by two principal complications related to specific properties of the phenomena under investigation. Firstly, the flux of these particles is very low (on average, only one particle with energy we consider arrives at one square kilometer per year). This implies impossibility of direct registration of primary particles, which interact in the upper layers of the atmosphere, with the help of flying detectors, and determines the necessarily indirect way of their studies with ground-based installations which detect extended atmospheric showers (EAS) caused by these particles. Moreover, even large ground-based detectors working for many years collect the number of events which is negligible as compared, for instance, to the number of astrophysical photons detected by a telescope in any other energy band. Secondly, 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 TeV), therefore the

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models which relate the EAS development to properties of the primary particle inevitably include extrapolation of interaction properties into yet unexplored domains of energy (and momentum transfer).

The experimental installations actively working at present may be separated, based on the techniques they use, into ground arrays of surface detectors (SD) and fluorescent telescope detectors (FD). SD detects particles of a EAS at the surface level. Detectors form an array with the spacing $\sim 1$ km and are capable to determine the lateral distribution function (LDF) of the particle density in the shower. FD is a telescope which detects ultraviolet emission caused by fluorescence of atmospheric nitrogen molecules which are excited by charged particles of the shower. SD registers a two-dimensional slice of an EAS only but it works independently of the weather conditions and time of the day and is able to detect various shower components (electromagnetic, muon, baryon). FD sees the longitudinal development of a shower but is able to register events in clear moonless nights only (roughly, this constitutes about 10% of time) and is sensitive to the electron component only. At the same time, SD detects mostly the periferic part of the shower while FD sees the central core (see Fig. I).

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

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

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

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

Together with past experiments which had already finished their work, these ones obtain sometimes results which are not in a full mutual agreement. Notably, in 2012, working groups have been created which include representatives of all three currently operating experiments. The first results of the work of these groups have been discussed at a conference in CERN last spring; the discussion in Sec. 3 will be based on them in a number of points.

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 will be used in the following section where experimental results are discussed. Independently of the EAS detection method, the processing of raw data allows to extract the 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 non-simultaneously. FD is able to directly fix the position of the plane containing the shower core and the detector position; in stereo, the core position is given by the intersection of two such planes; in case of observations by only one telescope, it is necessary to take into account the temporal development of the signal. The precision of the SD geometrical 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 with the growth of the effective area of the detector: SD stations are positioned at larger spacing and FD telescopes observe a larger volume in the atmosphere. The best-ever angular resolution ($68\%$ of events reconstructed with the precision not worse than $0.6^\circ$) has been achieved in the previous-generation experiment, HiRes, which operated two FD stations in stereo. For present-day experiments with large effective area this quantity is $\sim 1.5^\circ$.

Energy. The primary energy is reconstructed indirectly. In the SD case, the signal is recorded at each particular detector station, then the lateral distribution of the signal is compared to the expected one. This procedure of the energy determination introduces
considerable uncertainty related to the modelling of the expected signal for various energies. FD observes the shower core which carries the dominant part of the energy; this method allows one to estimate, on the basis of measurements, the total energy of electrons and positrons in the core and is thus often called calorimetric. One should note however that there remain significant sources of uncertainty 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 the statistical error of $\sim (15 - 20)\%$ and with the systematic uncertainty of $\sim 25\%$.

**The type of the primary particle.** Due to both considerable fluctuations in the development of EAS 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 problem are based on the study of particular EAS components (electromagnetic, muon, hadron, Cerenkov etc.) and of detailed properties of longitudinal and/or lateral shower development (depth of the maximal development, front shape etc.). Even probabilistic estimates which result from application of these methods are strongly model-dependent.

**Observables of an ensemble of EAS.** Three principal observables determined for each event make it possible to analyze the ensemble of showers and to obtain statistical information about UHECR properties, that is about the primary composition, the energy spectrum and the distribution of arrival directions. For the latter, one searches for deviations from an isotropic distribution at either large (global anisotropy) or small (clustering; correlation with potential sources) angular scales. Results of these studies will be discussed in the next section.

### 3 Review of experimental results

#### 3.1 Energy estimation and spectrum

UHECR energy spectra measured by various experiments are given in Fig. 2(a). Determination of the spectrum which is based on the absolute measurements of the primary-particle energy and, for FD, also on detailed simulation of the exposure, cannot be model-independent. In order to suppress both the arbitrariness related to the choice of model and the systematic errors, it has been suggested [1] that the reason for 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 EAS 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, one needs 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, $10^{17.5} \lesssim E \lesssim 10^{19.5} \text{ eV}$, both the shape and the normalization of the shifted spectra coincide; this fact strongly supports the approach. One may however see from Fig. 2(b) that this agreement is slightly worse at the highest energies.
Figure 2: The UHECR spectra (the particle flux $J(E)$) as 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 amounts [7] of the energy shifts are $E'/E = 0.652, 0.561, 0.911, 1.102, 0.906$, correspondingly.
For a long time, the interest in the UHECR physics was heated by the predictions by Greizen [8], Zatsepin and Kuzmin [9] of the cutoff expected in the spectrum of cosmic-ray protons at energies above $\sim 7 \times 10^{19}$ eV which correspond to the pion-production threshold in proton interactions with photons of the cosmic microwave background (CMB) radiation (the GZK effect); at the same time, EAS initiated by particles whose reconstructed energies exceeded $10^{20}$ eV have been observed experimentally (the first of these events had been detected by the Volcano Ranch experiment [10] even before the CMB was discovered). As one may see from Fig. 2, the existence of these events have been confirmed by all experiments; however, the latest data indicate the presence of the 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; because of that, we do not quote the numbers here. One should remember also that these results do not prove that the suppression is related to the GZK effect, nor they exclude a step-like continuation of the spectrum.

### 3.2 Primary composition

Presently, the question about the UHECR primary composition is open. For a few recent years, contradictory results of HiRes and PAO are under active discussion both at conferences and in the literature. While results of the former experiment are in a full agreement with the energy-independent mostly proton composition, the measurements by the latter indicate a graduate change towards heavier primary nuclei with the energy growth. Both analyzes used, as the principal observable, the depth $X_{\text{max}}$ of the maximal shower development, as determined by FD, and the amount of its fluctuations. Besides these two experiments, $X_{\text{max}}$ has been studied, with smaller statistics, with the FD data at TA and with the Cerenkov-light data in Yakutsk (in the latter case, the fluctuations have been also 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 from the direction on the celestial sphere. However, in 2012, the PAO collaboration presented (see Ref. [12]) a separate analysis of events arrived from the Southern and Northern celestial hemispheres (the equatorial part of the latter may be observed by all experiments); no signs of a systematic difference were found. The Northern experiments presently have not yet collected the amount of events sufficient for this kind of analysis.

Another reason suggested for a possible explanation of the contradiction in $X_{\text{max}}$ results is the difference in methodics of the data processing by PAO and Yakutsk versus HiRes and TA. While the value of $X_{\text{max}}$ of an individual shower is defined in a similar way by all groups, the study of the ensemble of showers proceeds differently: the former pair of experiments select, by means of imposing numerous cuts which reduce the number of events significantly, the most representative, minimum-bias sample in which the $X_{\text{max}}$ distribution should coincide with that of all EAS, both detected and missed in the sample. Contrary, the second pair consider the full set of detected EAS but take the selection effects into account in calculation of the theoretically expected values, $X'_{\text{max}}$, for a given particular sample. To add to the complication, HiRes made use of a slightly different, compared to PAO and Yakutsk, quantity which parametrizes 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 parametrized by the mean logarithm of their atomic mass, $\langle \ln A \rangle$. Unfortunately this analysis inevitably depends on the shower-development model which is used to relate observable parameters to $\langle \ln A \rangle$.

The results of this comparative analysis, which made use of the EAS parameters mentioned above as well as of 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 my opinion, the scatter of 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 $X_{\text{max}}$ results between the HiRes and PAO analyses does not exceed the difference between PAO $X_{\text{max}}$ and fluctuation results. Probably one should state that systematic errors still dominate over real effects in the studies of the primary composition.

To finalize the discussion of the chemical composition, note that, astrophysically, a significant amount of primary heavy nuclei looks less probable as compared to the (predominantly) proton composition since it requires 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 charge are accelerated more efficiently leads to the requirement of a (not observed experimentally) sharp jump both in the composition and in the full flux of cosmic particles at the energies which correspond to the maximal energy of accelerated protons.

3.3 (An)isotropy of the arrival directions

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

The global anisotropy of arrival directions is expected in the case when the observed cosmic-ray flux is due to a limited number of more or less nearby sources. This picture is relevant for two cases: either there is a significant overdensity of sources close to the observer or particles from distant sources do not reach us for some reason. The first case corresponds to the sources in our Galaxy. The second option takes place for astrophysical sources of protons with sub-GZK energies; the dominant contribution to the cosmic-ray flux at these energies should come from the sources inside the so-called GZK sphere with the radius of order 100 Mpc. Since the matter inside this sphere is distributed inhomogeneously, the astrophysical scenario with a large number of proton sources implies anisotropic distribution of the arrival directions. This distribution may 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 consist of, basically, 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 to deviations from isotropy, that is the data, being compatible with the isotropic distribution, does 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 recent results most important for astrophysics is the lack of statistically significant clustering of arrival directions at small scales. The search for clusters of events allows one to constrain the number of their sources in the nearby Universe: in the limit when there is only one source, the arrival directions would all concentrate in a single spot around it; contrary, for infinite number of sources, the distribution would be isotropic. A quantitative method, which results in a lower limit on the number of sources from the lack of clustering, has been developed in Ref. [23]; its somewhat more complicated version has been recently applied to the PAO results [24]. Reliable constraints on the number density of sources may be obtained for the highest energies where the flux is dominated by nearby
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 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. 

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 magnetospheres of supermassive black holes [26] allows one to satisfy the concentration bounds and to construct 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 isotropic distribution [22]; however, at higher energies, slight deviations from isotropy are observed which consist of excesses of events separated by the angular scale about $15^\circ$. In the PAO data, this excess is determined by a spot of events [28, 29] around a nearby radio galaxy Cen A. It may happen that this spot is responsible also for the effect of the correlation with the large-scale structure because Cen A is projected to a more distant but very numerous supercluster of galaxies. In the Northern hemisphere (TA), one does not see an evident spot but the excess in the autocorrelation function is present. Note that for $E > 10^{20}$ eV, the PAO and TA experiments have detected 6 events only, of which two 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] about 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 an 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 has a number of problems and is hardly consistent with the analyses of other observables (including the chemical composition and the global anisotropy) and with 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, as compared to Ref. [31], effect. The TA results [22] exclude the effect in its original strength [31] and are consistent both with the total absence of the effect and with the weak effect seen in the latest data [21].

4 Particle-physics applications

It were the cosmic rays which made it possible to discover many elementary particles in the past, and presently fundamental physics of particles and interactions continues to exploit information coming from cosmic-ray physics and astrophysics. The primary directions here are: to study hadronic interactions at energies an order of magnitude higher than achieved in accelerators; to search for unknown effects which influence the atmospheric shower development; 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 EAS (though LHC results, in particular those of a 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 to extract directly 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 the shower development.

4.2 New-physics searches

Let us turn now to a couple of (far from being unique but, in the author’s opinion, most interesting for today) examples of application of UHECR to the search and constraining of new-physics models, that is of particles and interactions assumed in theories which extend the Standard Model of particle physics (SM) 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 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 away from the 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, so this observation pointed to the existence of UHE neutral particles which travel for cosmological distances. A subsequent publication by the HiRes collaboration [44] confirmed this result with an alternative analysis method. 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, left to right: inelastic pp cross section from the models and from the TOTEM experiment data at the LHC energy, $\sqrt{s} = 7$ TeV [37] and $\sqrt{s} = 8$ TeV [38]; “p-air” cross section from the models and from the EAS analysis data by the PAO [39], $\sqrt{s} = 57$ TeV, and HiRes [40], $\sqrt{s} = 78$ TeV, experiments. Statistical and systematic uncertainties are shown in black and gray, respectively.
phenomenon cannot be explained within the frameworks of standard physics and astrophysics (see e.g. the discussion in Ref. [45]). Popular extensions of SM, e.g. supersymmetry, do not help as well. The only non-contradictory explanation of this effect, which helps also to solve some other astrophysical problems and may be tested experimentally, has been proposed in Ref. [46] and is based on the phenomenon of axion-photon oscillations. Unfortunately, the very effect has not yet been tested in a similar independent experiment: because of the worse angular resolution of the only installation (TA) which operates FD in the stereo mode, one needs 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: the PAO water tanks are almost insensitive to muon-poor EAS initiated by primary photons.

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

5 Conclusion

The UHECR physics remains, for decades, one of the most interesting fields at the intersection of astrophysics and particle physics. Despite a serious progress in the experiment, we presently cannot say a lot about the origin of particles with energies above $10^{19}$ eV, and only a few models of particle acceleration in astrophysical sources may 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 chemical composition of primary particles in this energy range are probably dominated by systematic errors and not by real physical effects. The physical reason of a systematic difference in the primary energy determination by means of different methods is still unknown. Some indications to possible manifestations of new physics in cosmic rays deserve a close attention.

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