Ultra High Energy Cosmic Rays: Spectral Signatures and Observations

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Abstract. We review the observations of Ultra High Energy Cosmic Rays (UHECR), focusing on the energy spectra as measured by HiRes, Telescope Array (TA) and Auger detectors. We found that highest energy Auger steepening does not agree with GZK cutoff, which is most probably explained by the nuclei mass composition detected by Auger. At present the difference in mass composition in Auger and HiRes/TA data remains the main unsolved problem of UHECR origin.

1. Introduction
The systematic study of Ultra High Energy Cosmic Rays (UHECR, \(E > 1 \times 10^{18} \text{ eV}\)) started in late fifties after construction of Volcano Ranch (USA) and Moscow University (USSR) arrays. Understanding of origin of particles with these energies still remains an unsolved problem of high-energy astrophysics. The precise energy spectrum of UHECR particles gives a key to origin of UHECR because it has the features which are the signatures of the primary particles, their propagation and sources.

The most natural primary particles, carriers of UHECR signal, are extragalactic protons. Interacting with CMB radiation, protons can produce pions in reactions

\[ p + \gamma_{\text{cmb}} \rightarrow N + \pi \]  

which cause the sharp steepening of the spectrum, so-called Greisen-Zatsepin-Kuzmin (GZK) cutoff [1]. Another interaction is given by production of electron-positron pairs:

\[ p + \gamma_{\text{cmb}} \rightarrow p + e^- + e^+ \]  

This interaction results in characteristic feature, steepening of the spectrum called pair-production dip [2]-[4]. Being a relatively faint feature, the dip is however clearly seen in the spectra observed by AGASA [5], Yakutsk [6, 7], Fly’s Eye [8], HiRes [9] and Telescope Array (TA) [10, 11]. In these experiments the pair-production dip is seen with good \(\chi^2\). In the Pierre Auger Observatory (PAO or Auger detector) [12, 13, 14] the dip is observed too, but with large \(\chi^2\), if compared with theoretical pair-production dip, and it can be explained in the different way.

An alternative explanation of the dip has been proposed by Hill and Schramm [15]. They interpreted the dip observed first in 1980s in terms of a two-component model; the low
energy component is either galactic or produced by Local Supercluster. The Hill-Schramm’s interpretation is widely accepted now, and the Auger-observed dip can be one proposed by Hill and Schramm.

The GZK cutoff is predicted at $E_{\text{gzk}} \sim 50$ EeV, and it is more difficult to observe because of low statistics at these energies. However, all three largest detectors, Auger, HiRes and TA observe the sharp steepening of the spectrum at energy close to $E_{\text{gzk}}$. The shape of the GZK feature is model dependent, and it is not easy to prove that discovered steepening is GZK cutoff indeed. There is the model independent part of the spectrum at energy 50 – 80 EeV, but this interval is too narrow to have a large statistics of observations. A reasonable model for the GZK shape is given by so-called universal spectrum, where UHECR sources are distributed homogeneously, and data of HiRes confirm this shape within the limited statistics this detector has at energy $E > 50$ EeV. Another signature of the GZK cutoff exists in the integral spectrum. The GZK cutoff there is characterised by model-independent energy $E_1/2 \approx 53$ EeV [2]. At this energy the spectrum calculated with pion energy losses included, becomes twice less than the power-law extrapolation from low energies. $E_1/2$ measured from the HiRes integral spectrum precisely coincides with theoretically predicted value. The above-considered features, pair-production dip and GZK cutoff, exist only for UHE protons. HiRes and TA arrays at energy $E \gtrsim 3$ EeV discover by the direct measurements the proton-dominated mass-composition, and these detectors found also the spectral features which are expected for proton composition: pair-production dip, GZK cutoff and $E_1/2$ in the integral spectrum of HiRes. However, the direct measurements of Auger detector show at $E \gtrsim 3$ EeV the nuclei composition with mean atomic number $A$ steadily increasing with energy. Not surprisingly the Auger energy spectrum shows the dip and cutoff which agree badly with these features calculated for proton spectrum. This conflict can be resolved only by future observations.

![Figure 1](image-url)  

**Figure 1.** Pair-production dip and GZK cutoff in terms of modification factors in comparison with Akeno-AGASA, HiRes, Yakutsk and TA observational data.
Meanwhile, in energy spectrum of all detectors there is a common feature, ankle observed at energy $E_a \approx 4.6$ EeV in HiRes and $(4.0-4.5)$ EeV in Auger. Starting from pioneering observations of Volcano Ranch detector this feature is interpreted as transition from galactic to extragalactic cosmic rays, though at present it is argued [3, 4] that this feature can be an intrinsic part of the dip. There are also some observational evidences against the above transition occurring at the ankle. In this paper the spectral features outlined above are analysed.

2. Pair-production dip

The pair-production dip is convenient to analyze in terms of modification factor $\eta(E)$ which is defined as the ratio of proton spectrum $J_p(E)$ calculated with all energy losses to the so-called unmodified spectrum $J_{unm}(E)$ in which only adiabatic energy losses (red-shift) are included:

$$\eta(E) = J_p(E)/J_{unm}(E)$$

(3)

Modification factor is an excellent characteristic of interaction signature. As one might see the interactions enter only numerator and thus they are not suppressed in $\eta(E)$, while most other phenomena enter both numerator and denominator and they are suppressed or even cancelled in modification factor. Property is especially pronounced for the dip modification factor. In figure 1 the predicted dip is shown in comparison with experimental data. Only two free parameters are used, $\gamma_g$ and the total normalization, for description more than 20 energy bins in each experiment.

Numerical position of GZK cutoff in figure 1 coincides well with theoretically expected $E_{gzk} \approx 50$ EeV, namely for HiRes it is equal to $E_{gzk} = (56 \pm 5 \pm 9)$ EeV and for TA $E_{gzk} = (48 \pm 1)$ EeV. For Auger detector it is noticeably lower $E_{gzk} = (29 \pm 2)$ EeV.

Could Auger and HiRes/TA data agree using the model-dependent comparison and allowed energy shift $\lambda$ of the bins within systematic uncertainties of the experiments? The answer to this question is illustrated by figure 2. We discuss first the dip in PAO spectrum [14] presented by the filled boxes in the left panel of figure 2. We use the model-dependent method in terms of $E^3 J(E)$ including the cosmological evolution $(1+z)^m$ up to $z_{max}$ as shown in the left panel of figure 2. Using two more free parameters $m$ and $z_{max}$ we can reach better agreement with the modified shape of the dip shown the solid curve in figure 2. Now we can shift the PAO energy bins by factor $\lambda$ reaching minimum $\chi^2$. For this $\lambda = 1.22$ is needed. As a result we obtain picture shown in the right panel of figure 2. Rescaled PAO data show not only excellent

Figure 2. Left panel: Comparison of the PAO energy spectrum (filled boxes) with the HiRes and TA data fitted by theoretical pair-production dip (solid curve). Right panel: Spectra after energy recalibration of the PAO data with $\lambda = 1.22$ (see the text).
Agreement with the shape of the theoretical pair-production dip (solid curve), but also good agreement with absolute fluxes of HiRes and TA.

We shall refer to this procedure as recalibration of the detector. Indeed, the pair-production dip has physically determined energy position, and shifting the observed energy bins to reach minimum $\chi^2$ means energy calibration of the detector using the dip as calibrator.

Recalibration with help of pair-production dip for all five detectors (HiRes, Telescope Array, PAO, AGASA and Yakutsk) is shown in figure 3. Recalibration factor $\lambda = 1$ for HiRes/TA is based on the scale factor which correctly describes the pair-production dip and GZK cutoff in differential and integral ($E_{1/2}$) spectra.

3. GZK cutoff

The pair-production dip and GZK cutoff are well seen in HiRes and TA data together with directly measured proton-dominated mass composition. The Auger energy spectrum with internal calibration of the fluorescent and ground detectors does not agree with the theoretically predicted shape of GZK cutoff (see figure 4).

Figure 3. Left panel: Original fluxes from all detectors (fluxes from HiRes and TA are approximately the same). Right panel: Spectra after energy recalibration by pair-production dip: $\lambda = 1$ for HiRes/TA, $\lambda = 1.22$ for PAO, $\lambda = 0.75$ for AGASA and $\lambda = 0.625$ for Yakutsk.

Figure 4. Comparison of Auger energy spectrum [14] with theoretically predicted GZK cutoff.
The Auger spectrum shown in figure 4 coincides perfectly well with the dip spectrum and after recalibration ($\lambda = 1.22$) with HiRes/TA absolute flux (see figure 2 and figure 3). Note however that disagreement of Auger data with GZK cutoff after recalibration still remains for the beginning of the GZK cutoff as well as for the three energy bins in energy interval 35 – 52 EeV. It means that highest energy steepening of Auger spectrum is not GZK cutoff. We could not reconcile the Auger cutoff shape with the GZK behavior by including in calculations different generation indices $\gamma_g$, low acceleration maximum energy $E_{\text{max}}$, local sources overdensity etc. This is a natural result if one takes into account that Auger mass composition is not proton-dominated.

4. Conclusions
The energy spectra remain the powerful tool to determine the origin of UHECR. The signature of UHE proton interaction with CMB, pair-production dip, is clearly seen in four experiments Yakutsk, Akeno-AGASA, HiRes and Telescope Array using only one free physical parameter $\gamma_g$. Dip has fixed energy position. Using the energy calibration of these detectors with help of the dip we obtain agreement in absolute fluxes measured by these detectors. For Auger detector this operation needs additionally included evolution. HiRes observes GZK cutoff in both differential and integral ($E_{1/2}$) spectra, and TA confirms GZK cutoff in differential spectrum. Auger spectrum can be brought into agreement with pair-production dip in model-dependent approach, e.g. using cosmological evolution of the sources, but disagreement with GZK cutoff remains in all our calculations. This result correlates with nuclear composition found by this detector.

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