On the status of the dip in UHECR spectrum

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Abstract: The status of the pair-production dip as a spectral feature, produced by interaction of Ultra High Energy extragalactic protons with CMB is discussed.

Greisen-Zatsepin-Kuzmin (GZK) cutoff \cite{1} is the most spectacular prediction for Ultra High Energy Cosmic Ray (UHECR) spectrum, which status is still uncertain in the present observations. As physics is concerned, detection of the GZK cutoff means discovery of UHE proton interaction with CMB radiation. Another prediction for interaction of UHE protons with CMB is $e^+e^-$-production dip, the spectral feature originated due to electron-positron pair production by extragalactic UHE protons propagating through CMB: $p + \gamma_{\text{CMB}} \rightarrow p + e^+ + e^-$. Originally proposed for diffuse spectrum in early work \cite{2}, this feature has been studied recently in Refs. \cite{3, 4}. An alternative explanation of the observed pair-production dip, widely discussed now \cite{5}, was first put forward in works \cite{6} and \cite{7} in terms of a two-component model as the transition from galactic to extragalactic cosmic rays.

Being quite faint feature, $e^+e^-$-production dip is not seen well in the naturally presented spectrum $\log J(E)$ vs. $\log E$. The dip is more pronounced when analyzed with help of the modification factor \cite{2, 8}, $\eta(E) = J_p(E)/J_p^{\text{unm}}(E)$, where $J_p(E)$ is the spectrum calculated with all energy losses included, and $J_p^{\text{unm}}(E)$ is the unmodified spectrum calculated with adiabatic energy losses only. The observed modification factor is given by $n_{\text{obs}} \propto J_{\text{obs}}(E)/E^{-\gamma_g}$, where $J_{\text{obs}}(E)$ is the observed spectrum and $\gamma_g$ is the exponent of the generation spectrum $Q_{\text{gen}}(E_p) \propto E_p^{\gamma_g}$ in terms of initial proton energies $E_p$.

The pair-production dip is clearly seen in the energy-dependence of $\eta(E)$ and is reliably confirmed \cite{3, 4, 9} by observational data, as Fig. 1 shows. The comparison of the predicted dip with observational data includes only two free parameters: slope of the generation spectrum $E^{\gamma_g}$ (the best fit corresponds to $\gamma_g = 2.7$) and normalization constant to fit the $e^+e^-$-production dip to the measured flux. The number of energy bins in the different experiments is 20 - 22. The fit is characterized by $\chi^2$/d.o.f. = 1.0 - 1.2.

The theoretical pair-production dip has two flattenings: one at energy $E_a \approx 1 \times 10^{18}$ eV and the other at $E_b \approx 1 \times 10^{19}$ eV. One can see that at $E < E_b$ experimental modification factor as measured by Akeno and HiRes exceeds the theoretical modification factor. Since by definition modification factor must be less than one, this excess signals the appearance of a new component of cosmic rays at $E < E_b = 1 \times 10^{18}$ eV, and thus the transition from extragalactic to galactic cosmic rays, starting at energy $E_b$.

The second flattening automatically explains the \textit{ankle}, the feature seen in all experiments starting from Haverah Park in the end of 70s.

The position and shape of the dip is robustly fixed by interaction with CMB and can be used for energy calibration of the detectors. The
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Figure 1: The predicted pair-production dip in comparison with Akeno-AGASA, HiRes, Yakutsk and Auger data [10]. While the first three experiments confirm dip with good $\chi^2$/d.o.f. $\approx 1.0 - 1.2$, the comparison with Auger data is inconclusive, because at present Auger does not present data at $E \leq 3 \times 10^{18}$ eV needed for confirmation of the dip. The data of Fly’s Eye [10] (not presented here) confirm the dip as AGASA, HiRes and Yakutsk detectors do.

Figure 2: The fluxes from Akeno-AGASA, HiRes and Yakutsk detectors before and after calibration by the $e^+e^-$-production dip.
Figure 3: The dip-based prediction for diffuse spectrum for the Auger detector. The calculated dip is normalized by calibrated AGASA-Yakutsk data as shown in Fig. 2. The diffuse energy spectrum is displayed for different distances \(d\) between sources in the range \(1 - 60\) Mpc. This presents the largest theoretical uncertainties in energy range \((1 - 7) \times 10^{19}\) eV. The both uncertainties in spectrum in the interval \((1 - 7) \times 10^{19}\) eV due to dip-based calculations and measurements by AGASA, Hires and Yakutsk detectors are small, and Auger should observe the beginning of the GZK cutoff at \(E \geq 5 \times 10^{10}\) eV, as shown here.

systematic errors in energy measurements are high, from 15% in AGASA to 50% in Auger. To calibrate each detector we shift the energies by factor \(\lambda\) to reach minimum \(\chi^2\) in comparison with theoretical dip. We obtain these factors as \(\lambda_A = 0.9, \lambda_{YA} = 0.75\) and \(\lambda_{Hi} = 1.2\) for AGASA, Yakutsk and HiRes detectors, respectively. Recently, AGASA collaboration has reduced their energies by 10% indeed, based on reconsideration energy determination. The fluxes given by different experiments agree with each others in a most precise way (see Fig. 2).

Concerning the calibration two remarks are in order.

i) After calibration the discrepancy between AGASA and HiRes data at the highest energies diminishes to the level of 2.5 \(\sigma\), but the AGASA excess over the theoretical flux with the GZK cutoff remains statistically significant. The better agreement between highest energy AGASA and HiRes data implies some trial theoretical spectrum between AGASA and HiRes data.

ii) One can see that calibration with help of the pair-production dip implies decreasing energies measured by on-ground methods (\(\lambda_A = 0.9\) and \(\lambda_{YA} = 0.75\)) and increasing the energies measured by fluorescent method (\(\lambda_{Hi} = 1.2\)). It might be considered as an indication to the difference in measuring energies by these two methods.

The predicted shape of the \(e^+e^-\)-production dip is quite robust [3, 9]: it is modified very weakly when the discreteness in the source distribution and their inhomogeneities are taken into account, and different regimes of propagation (from rectilinear to diffusive) are considered. The cosmological evolution of the sources, e.g. with parameters inspired by observations of Active Galactic Nuclei (AGN), also results in the same shape of the dip. The pair-production dip is modified strongly when the fraction of nuclei heavier than protons is
high at injection, which imposes some restrictions on the mechanisms of acceleration operating in UHECR sources [9]. The shape of acceleration spectrum needed for the $e^+e^-$-production dip agrees with standard ones $\gamma_g = 2$ for non-relativistic shock acceleration or $\gamma_g = 2.2 - 2.3$ for relativistic shock. The effective $\gamma_g = 2.7$ needed at ultra high energy is naturally explained by distribution of sources over maximum energy of acceleration or luminosity [3, 9, 11].

On the basis of the predicted dip and the calibrated data of all detectors shown in Fig. 2 we can make the predictions for spectrum measured by Auger detector shown in Fig. 3.

In the energy interval $(0.1 - 8) \times 10^{19}$ eV the uncertainties in the predicted spectrum are relatively small and are mainly given by uncertainties in distances between sources. These uncertainties dramatically increase at $E \gtrsim 1 \times 10^{20}$ eV. In Fig. 3 the spectra are shown for proton-dominated flux with distances between sources in the range $(1 - 60)$ Mpc. Therefore the beginning of the GZK cutoff up to $E \approx (7 - 8) \times 10^{19}$ eV is predicted in the dip-based model with small uncertainties. At larger energies the spectrum of GZK feature is very model dependent: apart from distances between sources it depends on fluctuations in luminosities of the nearby sources and in distances between them, and by maximum acceleration energy $E_{\text{max}}$ (see [3] for calculations).

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