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# Evidence for UHECR protons interacting with CMB

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Ultrahigh energy (UHE) extragalactic protons propagating through cosmic microwave background radiation (CMB) acquire the spectrum features in the form of the dip and the Greisen-Zatsepin-Kuzmin (GZK) cutoff. We have performed the analysis of these features in terms of the modification factor. In the case of the dip this analysis is weakly model-dependent. The excellent agreement of the dip with experimental data (AGASA, HiRes and Yakutsk) is the strong evidence that UHE cosmic rays observed at energies $1 \times 10^{18}$ eV – $4 \times 10^{19}$ eV are extragalactic protons propagating through CMB. The dip is also present in case of diffusive propagation in magnetic field.

## 1. Introduction

The nature of signal carriers of UHECR is not yet established. The most natural primary particles are extragalactic protons. Due to interaction with the CMB radiation the extragalactic UHE protons are predicted to have a steepening of energy spectrum, so called GZK cutoff [1]. Dip is another signature of extragalactic protons in the spectrum [2]-[5], which is produced due to $p + \gamma_{\rm CMB} \to p + e^+ + e^-$ interaction at energy centered by $E \approx 8 \times 10^{18}$ eV. Being relatively faint feature, dip is however clearly seen in the spectra observed by AGASA, Fly's Eye, HiRes and Yakutsk arrays (see [6] and [7] for the data). We argue here that it can be considered as the confirmed signature of interaction of extragalactic UHE protons with CMB.

The measurement of the atmospheric height of EAS maximum, $X_{\rm max}$, in the HiRes experiment gives another evidence of the proton composition of UHECR at $E \geq 1 \times 10^{18}$ eV [8]. Yakutsk [9] and HiRes-Mia [10] data also favour the proton composition at $E \geq 1 \times 10^{18}$ eV, while Fly's Eye and Akeno data indicate the mixed chemical composition (see [11] for review).

Below we shall analyze the features in UHE proton spectrum using basically two assumptions: the uniform distribution of the sources in the universe and the power-law generation spectrum.

## 2. Dip as a signature of the proton interaction with CMB

The analysis of the dip is convenient to perform in terms of *modification factor* [3]. The modification factor is defined as a ratio of the spectrum $J_p(E)$, with all energy losses taken into account, to unmodified spectrum $J_p^{\rm unm}$, where only adiabatic energy losses (red shift) are included, $\eta(E) = J_p(E)/J_p^{\rm unm}(E)$.

The *dip* is more reliable signature of interaction of protons with CMB than GZK feature. The shape of the GZK feature is strongly model-dependent: it is more flat in case of local overdensity of the sources, and more steep in case of their local deficit. It depends also on the discreteness in source distribution, on fluctuations in the distances between sources and on fluctuations of luminosities of the sources. The shape of the *dip* is fixed and has a specific form which is difficult to imitate by other mechanisms. The dip is also present in case of diffusive propagation in magnetic field [12]. The protons in the dip are collected from the large volume with the radius about 1000 Mpc and therefore the assumption of uniform distribution of sources within this volume is well justified. In contrast to this well predicted and specifically shaped feature, the cutoff, if discovered, can be produced as the acceleration cutoff. Since the shape of both GZK cutoff and acceleration cutoff is model-dependent, it will be difficult to argue in favour of any of them.

The problem of identification of the dip depends on the accuracy of observational data, which should confirm the specific (and well predicted) shape of this feature. Do the present data have the needed accuracy?

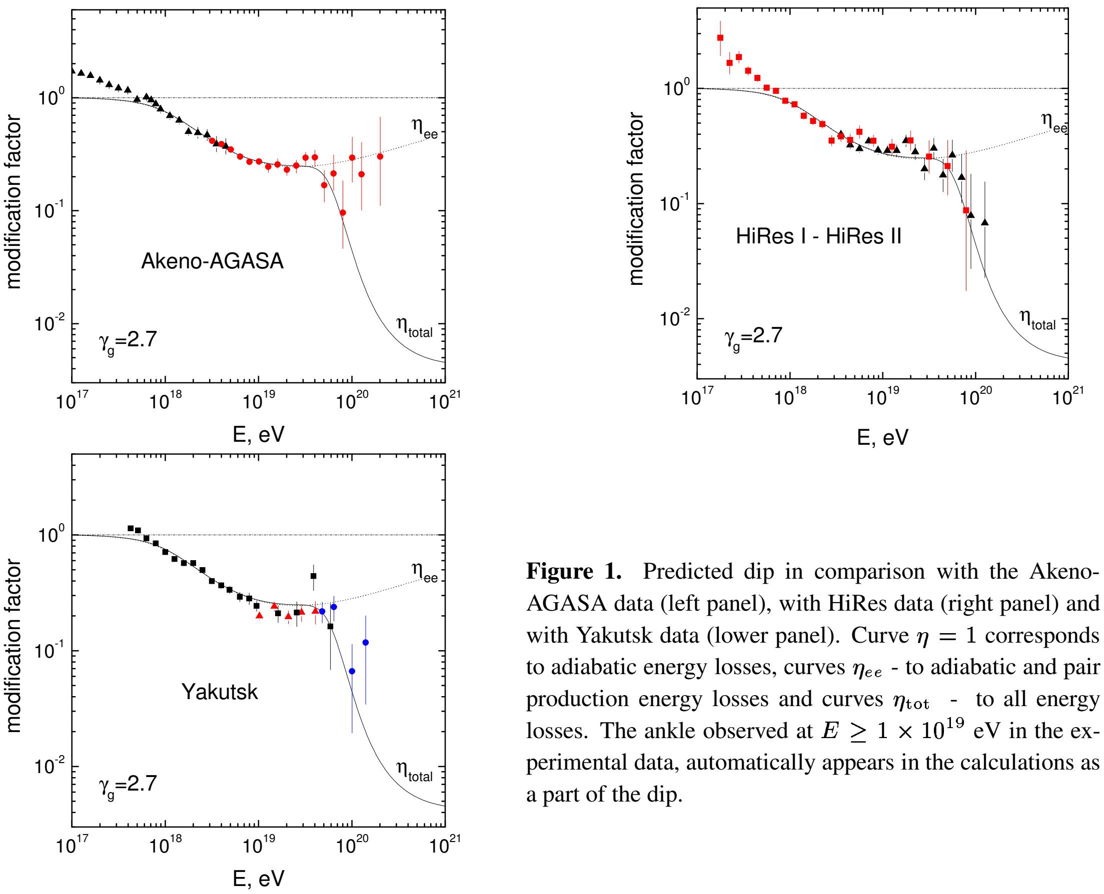

**Figure 1.** Predicted dip in comparison with the Akeno-AGASA data (left panel), with HiRes data (right panel) and with Yakutsk data (lower panel). Curve $\eta = 1$ corresponds to adiabatic energy losses, curves $\eta_{ee}$ - to adiabatic and pair production energy losses and curves $\eta_{\rm tot}$ - to all energy losses. The ankle observed at $E \geq 1 \times 10^{19}$ eV in the experimental data, automatically appears in the calculations as a part of the dip.

The comparison of the calculated modification factor with that obtained from the Akeno-AGASA, HiRes and Yakutsk data, using generation index $\gamma_g = 2.7$, is given in Fig. 1. It shows the excellent agreement between predicted and observed by AGASA modification factors for the dip. The predicted modification factor agrees with HiRes and Yakutsk data also very good. The good agreement of the shape of the dip $\eta_{ee}(E)$ with observations is a strong evidence for extragalactic protons interacting with CMB. This evidence is confirmed by the HiRes data on the mass composition. The observation of the dip should be considered as independent evidence in favour of proton-dominated primary composition. In Fig. 1 one observes that at $E < 1 \times 10^{18}$ eV the agreement between calculated and observed modification factors becomes worse and at $E \leq 4 \times 10^{17}$ eV the observational modification factor becomes larger than 1. Since by definition $\eta(E) \leq 1$, it signals about appearance of another component of cosmic rays, which is naturally galactic cosmic rays. The condition $\eta > 1$ means the dominance of the new (galactic) component, the transition occurs at higher energy.

## 3. Extragalactic nuclei as UHECR primaries

Does modification factor for nuclei differ from the proton dip?

We calculated the modification factor for iron and helium nuclei, considering the propagation of the nuclei with energy losses taken into account.

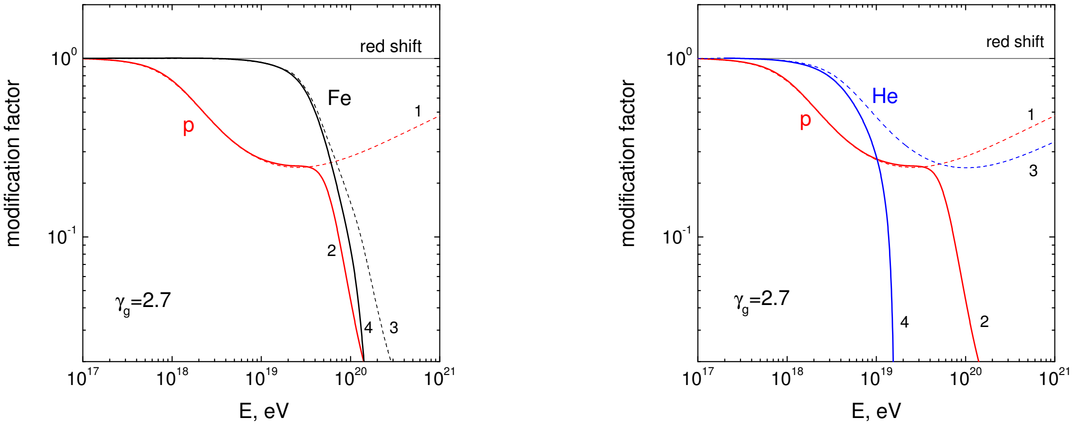

**Figure 2.** Modification factor for iron nuclei (left panel) and helium nuclei (right panel) in comparison with that for protons. Curve $\eta = 1$ corresponds to adiabatic energy losses. Proton modification factors are given by curve 1 (adiabatic and pair production energy losses) and by curve 2 (total energy losses). In both panels modification factors for nuclei are given by curves 3 (adiabatic and pair production energy losses) and by curves 4 (with photodissociation included).

In Fig. 2 the modification factors for nuclei are shown as function of energy in comparison with modification factors for protons. Comparison with Fig. 1 clearly shows that even small admixture of any nuclei in the primary extragalactic flux upsets the good agreement of the proton dip with observational data (see also [13]). From Fig. 2 one can see that fraction of nuclei in the primary flux should be less than $10 - 20\%$.

## 4. Transition from galactic to extragalactic cosmic rays.

We study this transition coming up-down the energy scale. In all regimes, from rectilinear to diffusion, there is the characteristic energy $E_c = 1 \times 10^{18}$ eV [5, 12], where extragalactic spectrum flattens (or $E^3 J_p(E)$ falls down). This energy of beginning of transition from extragalactic to galactic cosmic rays is determined by fundamental energy $E_{eq}$, where the energy losses due to redshift and $e^+e^-$ pair production are equal [12]. These energies are connected as $E_c = E_{eq}/(1+z_{eff})^2$, where $z_{eff} \approx 1.4$ is redshift of the epoch of production for a proton with energy $E_c$. Falling-down of extragalactic "flux" $E^3 J_p(E)$ with diminishing energy, results in the appearance of galactic flux, and thus the transition occurs at the second knee $E_{2kn}$, which should be below $E_c \sim 1 \times 10^{18}$ eV, as observed. Quantitatively, the transition from extragalactic protons to the galactic cosmic rays (iron nuclei) is described in references [12, 14].

In contrast to this picture, the transition at the ankle suffers two problem. The knees observed for protons, helium and carbon imply the iron knee at $6.5 \times 10^{16}$ eV, for which there are indications from KASCADE data. It means that iron nuclei at $E \geq 1 \times 10^{17}$ eV disappear from the Galaxy. Then how the gap between $1 \times 10^{17}$ eV and $1 \times 10^{19}$ eV, where extragalactic protons appear according to the ankle model, is filled?

Protons disappear even earlier, at $E \geq 3 \times 10^{15}$ eV, while at $E > 1 \times 10^{17}$ eV they are seen even in the Akeno data at level higher than 10%. Where they come from?

## 5. Conclusions

The dip is the most remarkable feature of interaction with CMB. The protons in this energy region are collected from the distances $\sim 1000$ Mpc, with each radial interval *dr* providing the equal flux. All density irregularities and all fluctuations are averaged at this distance, and assumption of uniform distribution of sources with average distances between sources and average luminosities becomes quite reliable. The dip is confirmed by Akeno-AGASA, HiRes and Yakutsk data with the good accuracy (see Figs 1). As one can see from Fig. 2, presence of even small $(10 - 20\%)$ fraction of extragalactic nuclei in the primary flux upsets this agreement.

We interpret the excellent agreement of the calculated dip with the observations as an independent evidence that observed primaries at energy $1 \times 10^{18} - 4 \times 10^{19}$ eV are extragalactic protons. This evidence is the complementary one to the direct measurements (now contradictive) of chemical composition.

At energy $E < 4 \times 10^{17}$ eV the modification factor from the Akeno and HiRes data exceeds 1, and it signals about dominance of another cosmic ray component, most probably the galactic one. It agrees with transition from galactic to extragalactic component at the second knee $E \sim 1 \times 10^{18}$ eV. This conclusion is confirmed by the recent HiRes data on mass composition [8] and indirectly by the KASCADE data (see [14] for the detailed analysis). When energy drops down below $E < 1 \times 10^{18}$ eV, there starts a gradual transition from extragalactic protons to galactic heavy nuclei.

## 6. Acknowledgements

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## References

[1] K. Greisen, Phys. Rev. Lett. **16**, 748 (1966); G. T. Zatsepin, V. A. Kuzmin, Pisma Zh. Experim. Theor. Phys. **4**, 114 (1966).

[2] C. T. Hill and D. N. Schramm, Phys. Rev. D **31**, 564 (1985).

[3] V. S. Berezinsky and S. I. Grigorieva, Astron. Astrophys. **199**, 1 (1988).

[4] T. Stanev et al., Phys. Rev. D **62**, 093005 (2000).

[5] V. Berezinsky, A. Z. Gazizov, S. I. Grigorieva, hep-ph/0204357; V. Berezinsky, A. Z. Gazizov, S. I. Grigorieva, astro-ph/0210095; V. Berezinsky, A. Z. Gazizov, S. I. Grigorieva, Phys. Lett. B, **612** 147 (2005).

[6] M. Takeda *et al.* [AGASA collaboration], Astropart. Phys. **19**, 447 (2003). N. Hayashida *et al.* [AGASA collaboration], Phys. Rev. Lett. **73**, 3491 (1994); K. Shinozaki and M. Teshima [AGASA collaboration], Nucl. Phys. B (Proc. Suppl.) **136**, 18 (2004); R. U. Abbasi *et al.* [HiRes collaboration], Phys. Rev. Lett. **92**, 151101 (2004); R. U. Abbasi *et al.* [HiRes collaboration], Astropart. Phys. **23**, 157 (2005); D. J. Bird *et al.* [Fly's Eye collaboration], Astrophys. J. **424**, 491 (1994); V. P. Egorova *et al.* [Yakutsk collaboration], Nucl. Phys. B (Proc. Suppl.) **136**, 3 (2004).

[7] M. Nagano and A. Watson, Rev. Mod. Phys. **72**, 689 (2000).

[8] R. U.Abbasi et al., Astrophys. J. **622**, 910 (2005).

[9] A. V. Glushkov *et al.* (Yakutsk collaboration) JETP Lett. **71**, 97 (2000).

[10] T.Abu-Zayyad et al., Astrophys. J., **557**, 686 (2001); T.Abu-Zayyad et al., Phys. Rev. Lett. **84**, 4276 (2003).

[11] A. Watson, Nucl. Phys. B (Proc. Suppl.), **136**, 147 (2004).

[12] R. Aloisio and V. Berezinsky, Astrophys. J. **612**, 900 (2004) and Astophys. J. **625**, 249 (2005).

[13] D. Allard et al., astro-ph/0505566.

[14] V. Berezinsky, S. Grigorieva and B. Hnatyk, Astropart. Physics, **21**, 617 (2004).