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40 years of the GZK problem

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«**КОСМИЧЕСКИЕ ЛУЧИ СВЕРХВЫСОКИХ ЭНЕРГИЙ И ИХ ИСТОЧНИКИ**»

Основная цель III Международного рабочего совещания «Космические лучи сверхвысоких энергий и их источники» - объединить усилия теоретиков и экспериментаторов в поиске решений загадок космических частиц самых высоких энергий, как давно известных, так и появившихся в новых, более точных экспериментальных данных. В этом году Совещание будет посвящено 40-летию проблемы Грейзена-Зацепина-Кузьмина, связанной с обрезанием спектра космических лучей из-за взаимодействия протонов высоких энергий с реликтовым излучением. Хотя прошло 40 лет с момента предсказания такого обрезания, сделанного, в частности, сотрудниками ИЯИ в 1966 году, вопрос о его наличии до сих пор не решен. Эта проблема продолжает стимулировать новые открытия и идеи как в теории, так и в эксперименте. В буклете переиздаются оригинальные работы и публикуется ряд материалов к конференции.

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Dear colleagues,

Let me welcome you in the Institute for Nuclear Research (INR) of the Russian Academy of Sciences at the 3rd International Workshop on Ultra-high-energy cosmic rays and their sources. This year, the Workshop is devoted to the 40th anniversary of the publication of two seminal papers where the interaction of ultra-high-energy protons with the cosmic microwave background was considered and the cut-off of the spectrum of cosmic rays was predicted for the first time. After four decades, this prediction still heats up the interest in the studies of high-energy cosmic rays (UHECR), both experimental and theoretical. I hope that the Workshop will help to shed more light on numerous problems in this interesting area.

Victor Matveev,
Academician,
Director of INR,
Chairman of the Organizing Committee

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UHECR and a Renaissance in Cosmic Ray Investigations

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60th October Anniversary Prospect 7a, Moscow 117312, Russia

This is a kind of a Foreword addressed to all the participants of The III-rd International Workshop '40 Years of the GZK problem'.

First of all before coming to the main body of my talk I would like to show you the famous picture of the founder of cosmic ray physics Victor Hess taken in 1912 where he is shown at his balloon (Fig.1). The very story of the so-called GZK cut-off originated with the discovery by Penzias and Wilson (1965) of the Cosmic Microwave Background radiation (CMB) with temperature of about 3K (more exactly 2.7K). It was soon understood by K. Greisen (1966) and simultaneously by G. Zatsepin and V.K. (1966) that the Universe is not anymore an empty one but rather it is filled in by the photon gas and is not anymore transparent for cosmic rays of high energies.

Figure 1: In a balloon at an altitude of 5000 metres, Victor Hess, the father of cosmic ray research, discovered «penetrating radiation» coming from space

Now I would like to show you a short picture of a time scale of cosmic ray physics starting with the very beginning (Fig.2). One might see how many years it took to get into the experimental investigations of ultra high energy cosmic rays. It goes without saying that all the information about the primary high energy particles one gets from the study of extensive air showers.

Now I would like to remind you the general picture of elementary particle energy scales the humanity is dealing now with or may ever get some (experimental or observational) information on. On the Fig.3 one can see this schematic picture (courtesy F. Dydak (CERN)).

One can see that with the use of human technology (artificial sources of high energy par-

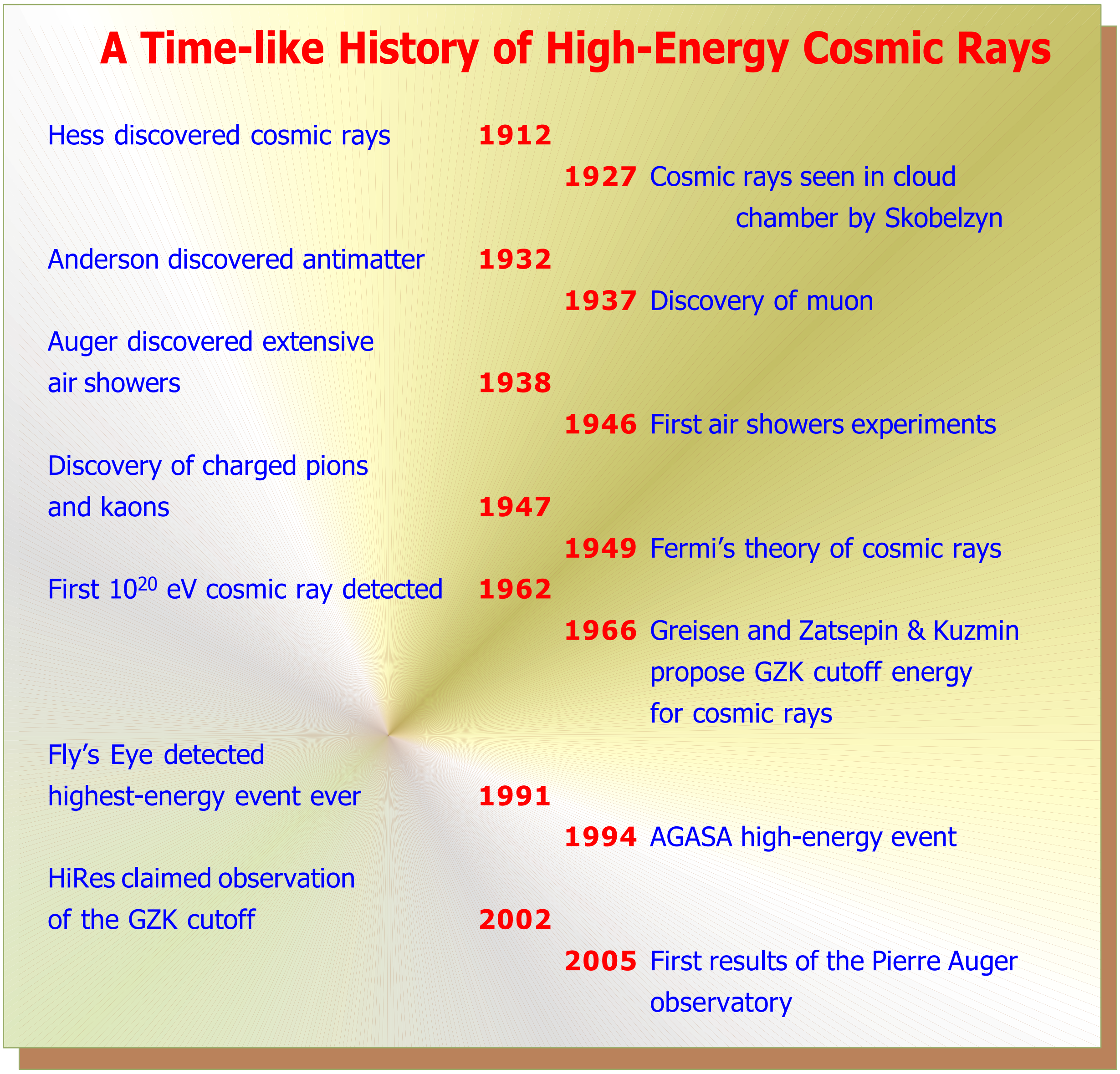

Figure 2: Time scale of cosmic ray physics

ticles -accelerators) as well as civilization Earth' energy resources we will never get into the ultra high energy region. But, with cosmic rays we are already have got dealing with energies as high as E ~ 10^{21} eV which I have to repeat seems to be never will be reached by means of our artificial human means.

Turning to the GZK expectations of the cut-off (suppression) of the cosmic ray energy spectrum, I should say that the very effect is quite simple. Starting with some ultra high energy, about $5{\cdot}10^{19}$ eV in the lab system, primary protons overcome the threshold energy for the reaction of photoproduction of pions, $p+\gamma>N\ \pi$'s} with a catastrophic energy loss. For protons of such a high energies the Universe becomes opaque one. That's it. About the same takes place for nuclei etc. The mean free path of protons with respect to collisions

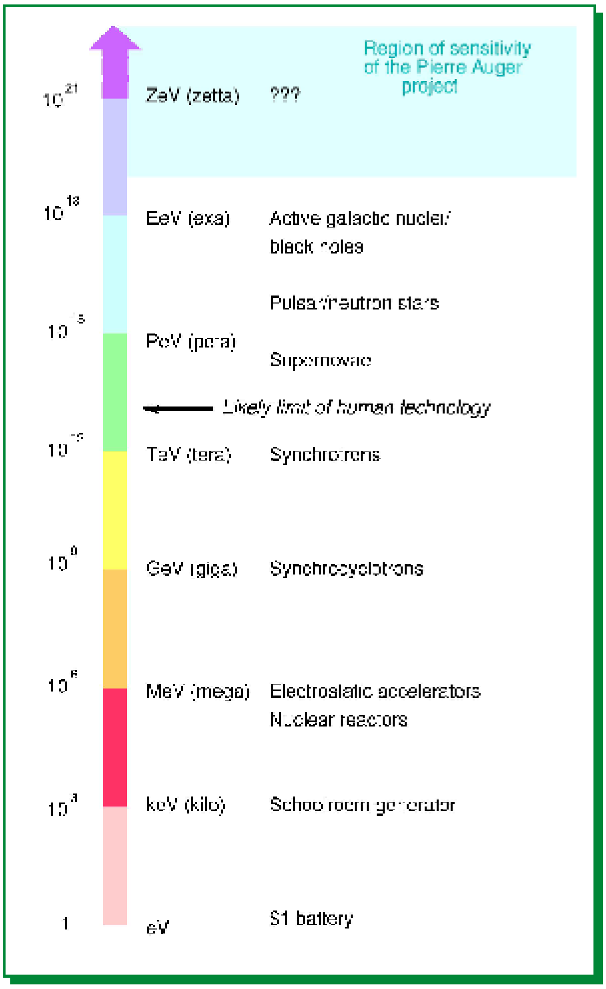

Figure 3: Energy scales of particle physics

with relic photons is about few Mpc, so the effective radius of (free) penetration of protons from a source to the observer (radius of collection) is of order R_{GZK}~50 Mpc.

Now it is time to show you one more illustration showing the astronomical distances scales where one is able to get an information by various radiations (see Fig.4, courtesy F. Dydak (CERN)).

It is probably the time for me to tell what I meant saying that we arrived now to the **Renaissance** of cosmic ray physics studies. At the very beginning the main goal of cosmic ray studies was mostly of particle physics interactions at high energies meaning. But then, after a tremendous progress in accelerator techniques the main interests in cosmic ray studies moved to the astrophysical aspects of the field, namely studies of origin, acceleration mechanisms, propagation of particles inside the Galaxy, and so on. Until the energies registered reached something about E ~ 10^{18} eV. There the cardinal change did occur. Cosmic rays with energies higher E ~ 10^{18} eV may carry some information on extragalactic space and origins, they are not deflected practically by magnetic fields, and so on. And, most important and new - they might be the carriers of information on the very distant sources and the very early epoch of the history of the Universe. One might guess that he has got to get into the **cosmological** meaning of the play! This might be the ultimate goal!

The observation of Ultra High Energy Cosmic Ray events with energies above 10^{20} eV by

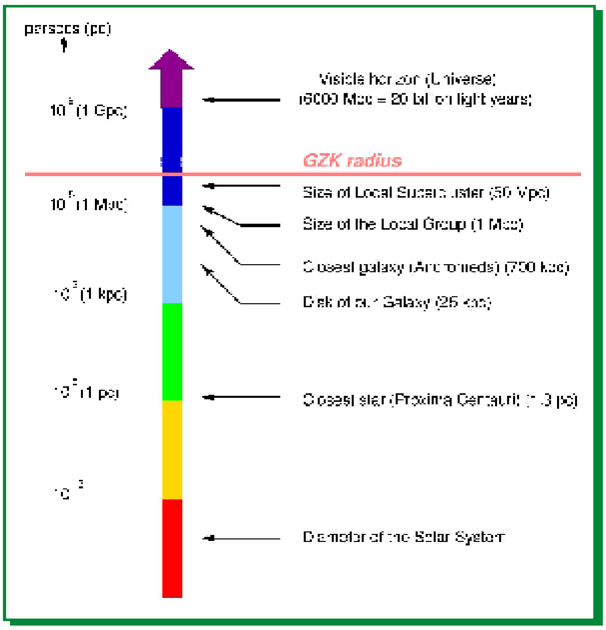

Figure 4: Distance scales of astronomy

AGASA is then one of the most intriguing puzzles. In case the events were observed indeed (with small enough uncertainty in energy determination) it would anyway mean we have got into the cosmological era of cosmic ray investigations. In fact, the confirmation of the existence of the GZK cut-off would simply mean that cosmic rays of UHE are mainly of and extragalactic origin, no matter what is their origin. In case the cut-off will not be confirmed one has conclude immediately that UHE cosmic rays originate somewhere nearby, within R_{GZK}~50 Mpc no matter again what is their origin.

The question now is what is the flux of UHECR after the expected GZK? There are two sets of experimental data. One shows the absence of the cut-off (AGASA) while the another one (HiRes, Auger) are more or less in accordance with the GZK predictions. Which data are more reliable? Might be, both if they do measure different things.

Data by AGASA show even more intriguing features. Namely, there is seemingly a small angle anisotropy in angular distribution of arrival directions of primary particles. Angular resolution of the installation is quite good, like 2.5°. That's very good. So, taking into account that UHECR particles don't deflect by magnetic fields as in Galaxy and in the extragalactic space, they point on the direction on the source. And one may put the arrival points (directions) on the sky map. But, you know, there are no objects on the sky in those directions! One may say that these particles came from NOWHERE! One more puzzle.

You know one is looking for deviation from the Standard Model (SM) of particle interactions by Weiberg-Salam. Here one has a kind of a certain paradox, probably nothing in common with SM. This should be resolved somehow. I will not come into the discussion of what follows. Other people will do it better than me.

One more thing is to be mentioned. It seems that we are at the possible recovery of the interest of the community in the particle interaction at super high energies by study the UHECR, once again (J. Takahashi (UAH), private communication, Dubna, April 2006).

I would like to finish with the beautiful piece of poetry by our beloved Russian poet Alexander Pushkin

О, сколько нам открытий чудных
Готовят просвещенья дух
И опыт, сын ошибок трудных,
И гений, парадоксов друг,
И случай, Бог изобретатель.[2]

I wish all the success to everybody and The Conference. Thank you for the attention.

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[2] *Oh so many wonderful discoveries the Wisdom Spirit brings to us, together with the Experience — the child of hard mistakes, and the Genius — the friend of paradoxes, and the Chance — the Lord the inventor.*

REPRINTED ORIGINAL WORKS

The original papers by Greisen (1966) and by Zatsepin and Kuzmin (1966) were cited several hundred times, and almost every contemporary study of ultra-high-energy cosmic rays refers to them. The papers are simple, elegant and short; they are certainly worth re-reading!

End to the cosmic-ray spectrum? (by Kenneth Greisen)

Kenneth GREISEN (born in 1918) – an expert in nuclear physics and high-energy astrophysics, notably in energetic cosmic rays, interaction of energetic particles with matter, hard X-ray and gamma-ray astrophysics. He was a staff member in Los Alamos Scientific Laboratory (1943-1946) and was an eyewitness of the nuclear-weapon tests; then he moved to the faculty of Cornell University (physics department from 1946, chairman of astronomy department from 1976, faculty dean from 1978). Now he is a Professor Emeritus in Cornell.

(photo from the Los Alamos badge, 1945)

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K. Greisen, Phys. Rev. Lett., vol. 16, p. 748-750, 1966.
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END TO THE COSMIC-RAY SPECTRUM?

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Cornell University, Ithaca, New York
(Received 1 April 1966)

The primary cosmic-ray spectrum has been measured up to an energy of 10^{20} eV,[1] and several groups have described projects under development or in mind[2] to investigate the spectrum further, into the energy range 10^{21}-10^{22} eV. This note predicts that above 10^{20} eV the primary spectrum will steepen abruptly, and the experiments in preparation will at last observe it to have a cosmologically meaningful termination.

The cause of the catastrophic cutoff is the intense isotropic radiation first detected by Penzias and Wilson[3] at 4080 Mc/sec (7.35 cm) and now confirmed as thermal in character by measurements of Roll and Wilkinson[4] at 3.2 cm wavelength. It is not essential to the present argument that the origin of this radiation conform exactly to the primeval-fireball model outlined by Dicke, Peebles, Roll, and Wilkinson[5]; what matters is only that the radiation exists and pervades the observable universe. The transparency of space at the pertinent wavelengths, and the consistency of intensity observations in numerous directions,

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give strong assurance that the radiation is indeed universal. The equivalent black-body temperature has been reported as $3.1 \pm 1°K$[6] and $3.0 \pm 0.5°K$.[4] For our discussion, we shall consider $T = 3.0°$, at which temperature the photon density is 548 cm^{-3} and the mean photon energy 7.0×10^{-4} eV. Although at this temperature the number of photons in the spectral range of the measurements ($\lambda \geq 3.2$ cm) is only 5×10^{-3} of the total, the slope of the spectrum is such that any reasonable extrapolation to shorter wavelengths would yield at least a substantial part of the 3° black-body photon density. Moreover, two indirect confirmations of the existence of the radiation have been reported: One lies in the slope of the isotropic part of the x- and gamma-ray spectrum[7] and the other in the absence of muon-poor air showers above 10^{16} eV.[8]

As the last statement implies, several consequences of the existence of the thermal radiation have quickly been noted. One is to provide a source of x rays and gamma rays by inverse Compton interactions with cosmic-ray electrons.[7,9,10] Another is to make the universe opaque to high-energy photons, above 2×10^{14} eV, because of positron-electron pair creation by photon-photon interactions.[8,11] A third effect is to deplete the density of energetic electrons by the energy losses in the inverse Compton interactions.[7,9] Hoyle[9] also considered the effect of the thermal radiation on cosmic-ray protons, but concluded that the time scale for energy degradation is greater than the expansion time of the universe for all protons up to 10^{21} eV. This conclusion is wrong because he only considered the proton Compton effect and neglected two stronger processes, namely pair creation and photopion production, which we now wish to examine.

The threshold energy for pion production by protons on photons of energy 7×10^{-4} eV (the mean energy of black-body radiation at 3°K) is 10^{20} eV, and some pion production occurs at lesser proton energies because of the high-frequency tail of the photon spectrum. The cross section rises rapidly above the threshold,[12] going through a peak exceeding 400 μb at the $\frac{3}{2}$, $\frac{3}{2}$ resonance (2.3×10^{20}-eV proton energy on 7×10^{-4}-eV photon), and descending thereafter to about 200 μb, about which minor wiggles occur owing to the superposition of higher resonances. With a mean cross section of 200 μb and a photon density of 550 cm^{-3}, the mean path for interaction is $(n\sigma)^{-1} = 9 \times 10^{24}$ cm. However, the distance scale for loss of energy is $L = (E/\Delta E)(n\sigma)^{-1}$, E being the initial proton energy and ΔE the energy loss per interaction. At the threshold for single-pion production, $\Delta E/E$ is only 0.13, but it rises to an average value of 0.22 at the $\frac{3}{2}$, $\frac{3}{2}$ resonance, and continues to rise thereafter as multiple pions are produced or more kinetic energy is given to a single pion. L is therefore on the order of 4×10^{25} cm, and the time scale for energy loss is 10^{15} sec, which is several hundred times less than the expansion time of the universe. L is also more than an order of magnitude less than the distance to the nearest quasar.

There is abundant evidence that above 10^{17} eV, the cosmic rays are not confined to the galaxy; the local intensity is a sample of the flux in a much larger sphere. If the sources of very high-energy particles are uniformly distributed in space and time, the effect of interactions like those described here is to deplete the spectrum by a factor equal to the ratio of the time scale for energy loss to one-third the expansion time. If, on the other hand, the sources of such particles exist only far back in time or at great distances, the depletion is much stronger. It may also be noted that if the primeval-fireball model is correct, going back in time raises the mean photon energy as $(1-t/T)^{-1}$ and the photon density as $(1-t/T)^{-3}$, T being the expansion time; thus the effect may be somewhat larger than our computations on a static model indicate.

It should be noted that the cut in the spectrum due to photopion processes is rather sharp, because of the steepness of the high-frequency tail of the Planck distribution. Only 1% of the photons have energies exceeding 3 times the mean value; also, close to the threshold the cross section is smaller than 200 μb and the fractional energy loss per interaction is a minimum. Therefore, below 3×10^{19} eV the process should have a completely negligible effect on the proton spectrum. As 10^{20} eV is approached, the effect should rise rapidly; and above 2×10^{20} eV, it should be a factor of several hundred. At present the data above 10^{19} eV are rather sparse, and the highest energy recorded is represented by a single event at 10^{20} eV.[1] A smooth representation and extrapolation of the spectrum gives an integral frequency of about one event on 100 km^2 in one year at energies above 2×10^{20} eV. If this number is cut by a factor of several hundred, owing to the γ-p reaction, the rate will be far too low to be detected by any of the methods yet proposed; even the one event recorded at 10^{20} eV appears surprising.

One cannot save the day for superhigh-energy cosmic rays by calling on heavy nuclei. The threshold for photodisintegration against photons of 7×10^{-4} eV is only 5×10^{18} eV/nucleon, and at 10^{19} eV/nucleon most of the photons can excite the giant dipole resonance, for which the cross section is on the order of 10^{-25} cm^2. At this energy the mean path for photodisintegration is on the order of 2×10^{22} cm, much less than the size of the galaxy. Even nuclei 5 times less energetic would be decomposed in a time short compared with the expansion time of the universe, owing to the high-frequency tail of the black-body spectrum.

Ordinary optical interstellar radiation can also produce γ-p photopions and heavy nucleus disintegrations, at energies 1000 times less than those discussed above; but the intergalactic optical photon density is smaller than that of the 3° radiation by a factor of about 5×10^4, and the mean paths are correspondingly longer. So the effect on the proton spectrum is negligible, but not the effect on the heavy nuclei: Above 10^{16} eV/nucleon the mean time for photodisintegration is an order of magnitude less than the expansion time. Nuclei confined in the galaxy encounter a higher density of optical photons and are fragmented much faster.

In addition to photopion interactions as a source of energy loss to high-energy protons, one should consider pair production by the thermal photons. The proton energy threshold for this reaction against photons of 7×10^{-4} eV is only 7×10^{17} eV. The energy loss in the laboratory system arises primarily from the small longitudinal momentum given to the proton in its rest system. At the threshold the fractional energy loss is $2m/M\simeq10^{-3}$, where m and M are the electron and proton masses. At higher energies the energy loss depends on the relative velocity of the electron and positron and the transverse momentum given to the proton, but the average energy loss in the laboratory is approximately constant, making the fractional energy loss $f\simeq10^{-3}/x$, where x is the ratio of the proton energy to its threshold value. The cross section with no screening is approximately $1.8\times10^{-27}(\ln x-0.5)$ cm^2. Therefore, the scale length for energy loss is given by $L=(nf\sigma)^{-1}\simeq10^{27}\times(\ln x-0.5)^{-1}$ cm. The minimum value of L occurs at $x=4.5$ or $E\simeq3\times10^{18}$ eV and is about half of the Hubble length. Thus, the effect on the primary spectrum is barely significant, creating a small depression (never exceeding a factor of about 3) in the interval 10^{18}-10^{20} eV.

Even this small depletion of the flux above 10^{18} eV, however, followed above 5×10^{19} eV by a stronger depression due to the photopion process, makes the observed[1] flattening of the primary spectrum in the range 10^{18}-10^{20} eV quite remarkable. The injection spectrum of the intergalactic flux must be much less steep than that of the galactic particles which dominate at lower energies.

The author expresses thanks for the hospitality of the Physics Department of the University of Utah, where this Letter was written.

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[1]J. Linsley, Phys. Rev. Letters 10, 146 (1963); and in Proceedings of the International Conference on Cosmic Rays, Jaipur 1963, edited by R. R. Daniel et al. (Commercial Printing Press, Ltd., Bombay, India, 1964-1965), Vol. IV, p. 77.

[2]C. B. A. McCusker and K. Greisen, in Proceedings of the International Conference on Cosmic Rays, London, September, 1965 (to be published); and S. Colgate, private communication.

[3]A. A. Penzias and R. W. Wilson, Astrophys. J. 142, 419 (1965).

[4]P. G. Roll and D. T. Wilkinson, Phys. Rev. Letters 16, 405 (1966).

[5]R. H. Dicke, P. J. E. Peebles, P. G. Roll, and D. T. Wilkinson, Astrophys. J. 142, 414 (1965).

[6]Private communication from Penzias and Wilson, reported in Ref. 4.

[7]J. E. Felten, Phys. Rev. Letters 15, 1003 (1965).

[8]R. J. Gould and G. Schréder, Phys. Rev. Letters 16, 253 (1966).

[9]F. Hoyle, Phys. Rev. Letters 15, 131 (1965).

[10]R. J. Gould, Phys. Rev. Letters 15, 511 (1965).

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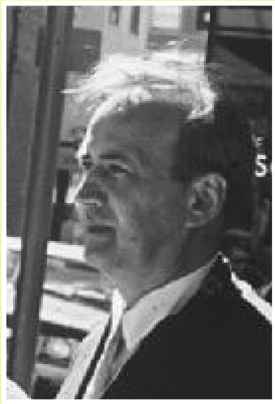
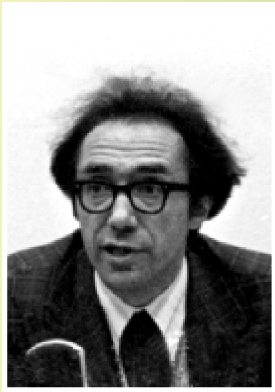
[12]R. R. Wilson, Phys. Rev. 110, 1212 (1958).

Upper limit on the spectrum of cosmic rays (by Georgy Zatsepin and Vadim Kuzmin)



Georgy ZATSEPIN (born in 1917) – a world-wide known physicist and astrophysicist. One of the authors of the discovery of electron-nuclear showers in cosmic rays and of the nuclear cascade process resulting in these showers. He pioneered the studies of interactions of ultrarelativistic particles with the photon gas; the measurements of basic characteristics of cosmic-ray muons and neutrino; the experiments on the ultra-high-energy muons and their interactions with nuclei. In the field of neutrino astrophysics, he studied mechanisms of production of high-energy cosmic neutrinos and neutrino emission from the stellar collapse in the Galaxy. He also developed new methods of solar-neutrino detection. In his paper of 1951, the pion photoproduction in the interactions of ultra-high-energy protons with a photon gas was studied and the fact that it may result in efficient loss of the proton energy was understood. These results were applied to the proton interactions with the cosmic microwave background in his famous paper with V. Kuzmin (1966). He worked in Lebedev Physical Institute and in the Institute for Nuclear Research (since it was established in 1970). Currently he leads the Department of high-energy leptons and neutrino astrophysics.

(photo from INR archives, 1968)



Vadim KUZMIN (born in 1937) – an outstanding theoretical physicist specializing in particle physics, cosmology, cosmic rays and neutrino astrophysics. He suggested a model of generating baryon asymmetry of the Universe in heavy-particle decays, was one of the pioneers of the electroweak baryogenesis, studied neutron-antineutron oscillations, suggested the gallium-germanium method of the solar neutrino detection, demonstrated the possibility of weak violation of the Pauli principle in quantum mechanics, studied non-accelerator mechanisms of ultra-high-energy cosmic-ray production. In 1966, jointly with G. Zatsepin, he predicted the cut-off in the cosmic-ray spectrum due to proton interaction with the cosmic microwave background. He worked in Lebedev Physical Institute and in the Institute for Nuclear Research (since it was established in 1970). Currently he leads the Particle astrophysics and cosmology division in the Department of theoretical physics.

(photo from INR archives, 1978)

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G.T. Zatsepin, V.A. Kuzmin, JETP Letters, vol. 4, p. 78-80, 1966.

UPPER LIMIT OF THE SPECTRUM OF COSMIC RAYS

G. T. Zatsepin and V. A. Kuz'min
P. N. Lebedev Physics Institute, USSR Academy of Sciences
Submitted 26 May 1966
ZhETF Pis'ma 4, No. 3, 114-117, 1 August 1966

Powerful isotropic thermal radiation of the Universe, having apparently a Planck distribution with temperature $T \approx 3°K$, has been observed in recent measurements [1,2]. The intensity of this radiation ($N \approx 550$ photons/cm^3, $kT \approx 2.5 \times 10^{-4}$ eV) is such that unique effects arise when cosmic rays of superhigh energy pass through it, specifically, cutoff of the cosmic-ray spectrum in the vicinity of 10^{20} eV.

At sufficiently high primary cosmic-ray proton energies $E_p \sim M_p c^2 (m_\pi c^2 / E_{ph,eff})$ [3], pion photoproduction processes occur when the protons interact with the photon gas, as a result of which the protons effectively lose energy ($\overline{\Delta E_p}/E_p \approx 20\%$) [4]. If the characteristic time for proton-phonon collision becomes sufficiently small compared with the lifetime of the cosmic rays with these energies in the Metagalaxy, as determined by other processes (for example, the expansion of the Universe), then effective cutoff of the cosmic-ray spectrum will take place. An exact analysis gives for the characteristic time of collision between a proton of energy $E_p \gg M_p c^2$ and a photon, at the photon-gas equilibrium temperature T,

$$\tau_{p\gamma} = \frac{2\pi^2 c^2 \hbar^3 \gamma^2}{kT\varphi}\ \mathrm{sec}, \quad \gamma = E_p/M_p c^2, \tag{1}$$

where

$$\varphi = \int_{E_{thr} \approx m_\pi c^2}^{\infty} dE E \sigma_{p\gamma}(E) \sum_{n=1}^{\infty} \frac{1}{n} \exp(-nE/2\gamma kT)\left(1 + \frac{1}{n}\frac{2\gamma kT}{E}\right), \tag{2}$$

$\sigma(E)$ is the total cross section for the absorption of a photon of energy E by interaction with a proton; this is principally the cross section for the photoproduction of π^0 and π^+ mesons

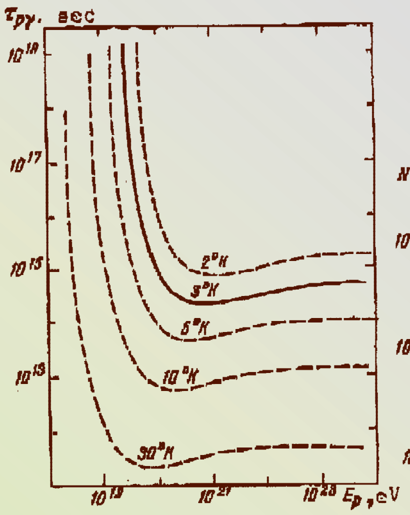

Fig. 1

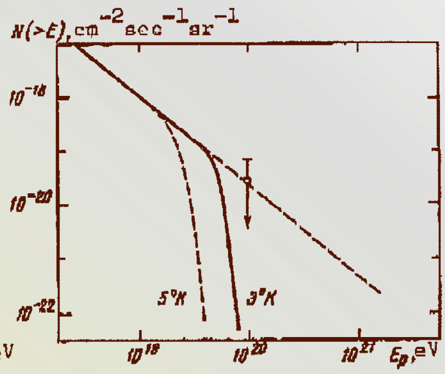

Fig. 2

at $E \leq 1$ BeV; at higher energies, up to the highest ones, we can assume $\sigma_{p\gamma}$ = const = 1×10^{-28} cm^2.

The values of $\tau_{p\gamma}$ calculated by formula (1) for different proton energies are shown in Fig. 1 for several photon gas temperatures, T = 2, 3, 5, 10, and 30. We see that at proton energies $E_p \gtrsim 10^{20}$ eV, proton interactions with the photon gas become quite frequent, $\tau_{p\gamma} \approx 10^7$ years. This means that at the age $t \gtrsim 10^8$ of the cosmic rays with energies under consideration, their initial spectrum should be cut off in the high-energy region, even if the acceleration mechanism had been sufficiently effective in producing particles having these energies. The question of the exact form of the cosmic-ray spectrum in the energy region $E_p \gtrsim 10^{19}$ eV calls for a detailed analysis combined with allowance for their generation, the expansion of the Universe, and the interaction of the cosmic rays with the photon gas at each stage of evolution of the Universe. The form of the spectrum will, of course, depend here on which stage of evolution of the Universe the cosmic-ray particles of superhigh energy were generated, and how rapidly the generation took place.

A study of the energy spectrum of the cosmic rays near its upper limit yields information not only on the processes of their generation, but also on the evolution of the Universe. The influence of the change of the photon-gas temperature T on the position of the limit of the cosmic-ray spectrum is approximately shown in Fig. 2; for simplicity, we have assumed here that the cosmic rays were produced in the Metagalaxy $\approx 10^9$ years ago. The previously obtained experimental point [5] constitutes one registered event with energy 10^{20} eV, with a probable error ~2 in the determination of the energy. The dashed curve corresponds to the case when the cosmic rays propagate during the 10^9 years in a photon gas having a temperature 5°K.

Notice should be taken of the disintegration of α particles and other nuclei [6] as they pass through metagalactic space. This occurs at an α-particle energy somewhat lower than the proton energy at which the pion photoproduction process begins. The rather large cross section of this process should lead to total disappearance of the nuclei from the cosmic rays at energies above 10^{19} eV.

<u>Note</u>. After writing this article, we received a preprint of a paper by K. Greisen, in which similar reasoning is presented and estimates agreeing with ours are obtained.

The authors take this opportunity to thank K. Greisen for communicating his unpublished results.

[1] A. A. Penzias and R. W. Wilson, Astrophys. J. <u>142</u>, 420 (1965).
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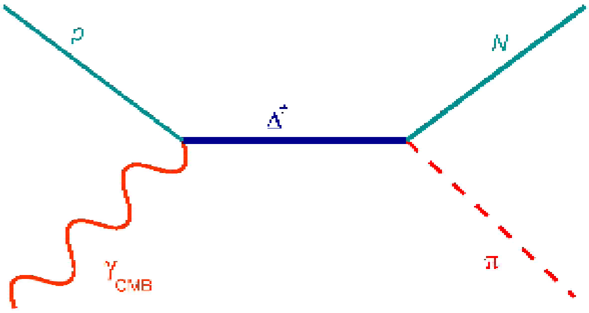
Creation of ideas…

THE GZK EFFECT

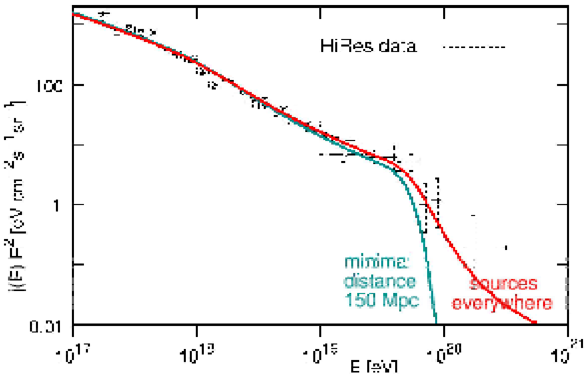
Ultra-high-energy protons interact with the cosmic microwave background photons. Above the threshold of multipion production, this interaction results in fast loss of energy of the proton:

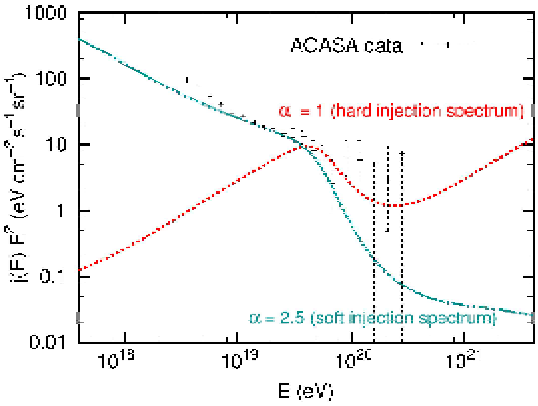


Multipion production on CMB:

- $E_p > 5 \cdot 10^{19}$ eV
- Mean free path ~10 Mpc
- $\Delta E_p / E_p \sim 20\%$
- Energy attenuation length: $R_{GZK} \sim 50$ Mpc

For a homogeneous distribution of sources in the Universe and falling injection spectra at the sources, these energy losses result in the GZK cut-off: a sharp break in the spectrum of observed cosmic rays at energies $E > 5 \cdot 10^{19}$ eV. Local overdensity of sources or very hard injection spectra would make the cut-off less pronounced.





The GZK cut-off is less pronounced for harder injection spectra (left) and sharper for large distances to the nearest source (right). j(E) is the particle flux, E is the energy. Plots adopted from papers by D. Semikoz et al.

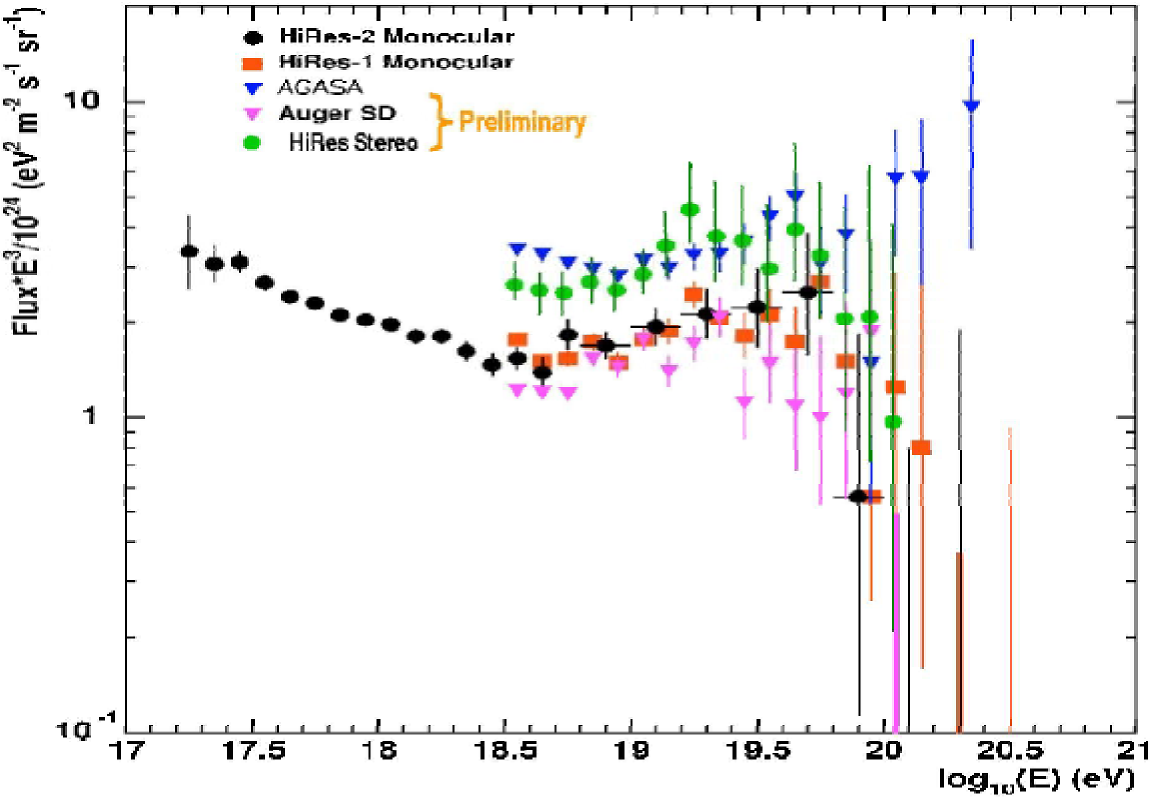
Numerous experiments (Volcano Ranch, Yakutsk, AGASA, Fly's Eye, HiRes and Pierre Auger) reported events with energies in excess of 10^{20} eV. If the primary particles of these air showers were protons, their sources should most probably be within R_{GZK} from the Earth. Presence of nearby sources is however insufficient to explain the absence of the cut-off suggested by the AGASA data (see the next page).

The cut-off is not a unique signature of interaction of ultra-high-energy protons with CMB. Among other signatures are:

- Dip in the spectrum at lower energies due to the interaction $p\gamma_{CMB} \rightarrow pe^+e^-$
- Bump in the spectrum at sub-GZK energies due to protons which lose energy in the GZK interaction
- Secondary photons and neutrinos from pion decays.

SUMMARY OF 2005 EXPERIMENTAL DATA ON THE COSMIC-RAY SPECTRA AT THE HIGHEST ENERGIES

Is the GZK cut-off observed by the cosmic-ray experiments? The plot with the combined data of different experiments demonstrates that currently we lack a definite answer.

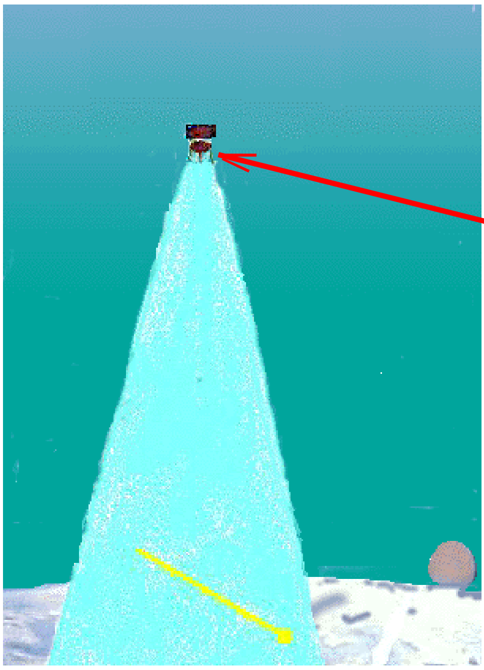


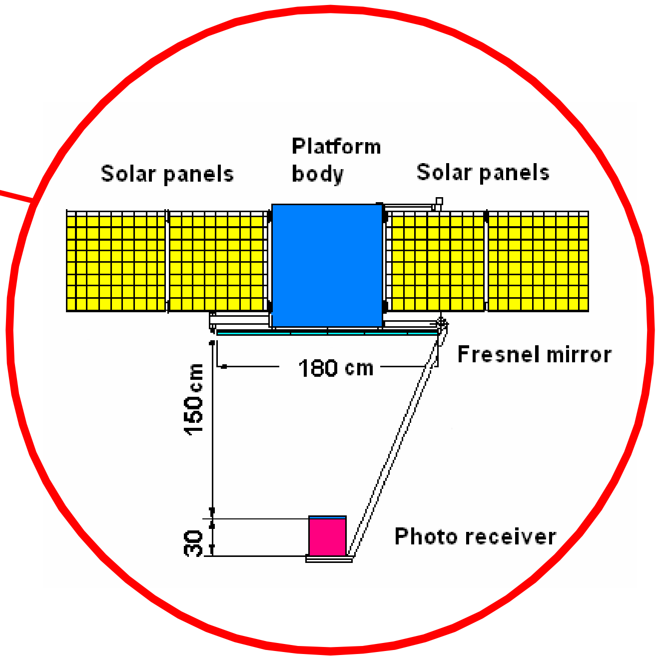
The plot is based on the data reported at the 29th International Cosmic-Ray Conference in Pune (August 2005; data from the rapporteur talk by S. Yoshida). Despite clear systematic difference between various experiments, one can see the dip and the bump in all spectra. However, low statistics at $E > 10^{20}$ eV does not allow us to answer whether the GZK cut-off is observed or not.

THE RUSSIAN PROGRAM OF SPACEBORN UHECR EXPERIMENTS

TUS: the Tracking Ultraviolet Set-Up

- Large mirror (narrow field of view) concentrator
- Studies of inclined (zenith angle 50° or more) air showers
- Uniform coverage of the sky suitable for large-scale anisotropy studies
- Energy threshold ~ 50 EeV
- Application for studies of other UV atmospheric flashes
- ! A prototype operates on board of the Tatiana satellite (launched in 2005)
- Full version to be launched in 2009 as a platform separated from the FOTON-4 satellite





Other projects

- KLYPVE – an extended version of TUS with a larger mirror (energy threshold 10 EeV)- to be accommodated at the Russian Segment of ISS.
- PAS – detection of radio emission from showers with a spaceborn antenna.
- LUCRETIUS – search of physical traces of UHE particles accumulated in the Lunar crust for billions of years.

THE HIGHEST ENERGY COSMIC RAYS AND THEIR SOURCES: A RUSSIAN-EUROPEAN PROJECT

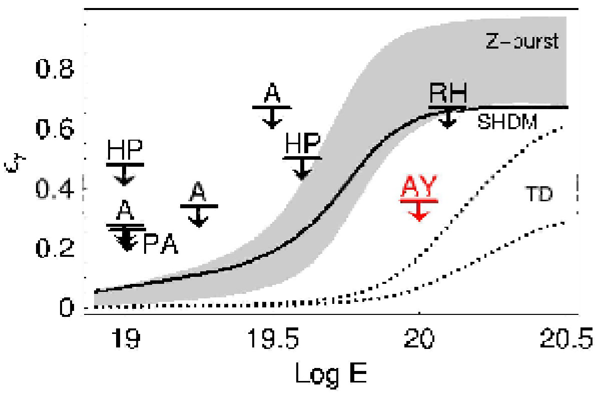
M. Teshima, S. Troitsky

In 2003, cosmic-ray scientists from Europe and Russia launched a joint project with the aim to unify the efforts of theoretical physicists and experimentalists in the study of cosmic particles with energies in excess of 10^{19} eV. At the time of the "GZK-40" Workshop, a coordination meeting of the participants of the project is scheduled.

The consortium consists of teams from Max Planck Institute for Physics, (Munchen, Germany); Universite Libre de Bruxelles (Belgium); Institute for Cosmophysical Research and Aeronomy (Yakutsk, Russia); Institute for Nuclear Research (Moscow, Russia) and Moscow State University (Russia).

The first results of the project include:

- The correlation between arrival directions of the cosmic rays observed by HiRes (stereo) and positions of bright BL Lac type objects
- Predictions for testing this correlation with future experiments
- A new method of precise studies of cosmic-ray composition
- The world-best limit on the gamma-ray fraction at E >10^{20} eV from the AGASA and Yakutsk data



Limits (95% C.L.) on the fraction ε_γ of photons in the integral cosmic-ray flux versus energy. The result of the present work (AY) is shown together with previous limits from Haverah Park (HP), AGASA (A), Risse et.al. (RH) and the Pierre Auger Observatory (PA). Also shown are predictions for the superheavy dark-matter (thick line) and topological-defect (necklaces, between dotted lines) models and for the Z-burst model (shaded area).

- A hybrid code for simulation of photon-induced air showers of extreme energies
- A study of small-scale fluctuations in air showers simulated without the thinning approximation
- An economic method to suppress artificial fluctuations due to thinning in air-shower simulations