The GZK Puzzle and Fundamental Dynamics

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Abstract

The conjecture that the GZK puzzle might be related with nontrivial structure of the inelastic defect of total cross sections in scattering from nuclei has been suggested.

1 Introduction: Ultra High Energy Cosmic Rays and Particle Physics

From the history of fundamental science everybody knows that Cosmic Rays Physics as a part of Astrophysics and Particle Physics especially based on accelerator studies have many common roots. In particular, many discoveries early in particle physics have been done in the study of cosmic rays. It is enough to remind that the researches in cosmic rays resulted in the discovery of such elementary particles as the positron $e^+$ in 1932, the muon – second charged lepton $\mu^\pm$ in 1937, the charged and neutral pions $\pi^\pm, \pi^0$, the strange particles kaons $K^\pm, K_L, K_S$ and $\Lambda$-hyperon in 1947, the antiproton, $\Xi^-$ and $\Sigma^+$ in 1952-1955.

In the very beginning of the second half of XX century a period of divergence between Cosmic Rays Physics and Particle Physics, both in methodology and in the places of interest, has been started. Particle physicists have taken the path of building the big accelerators and large detectors. The experiments at the Serpukhov accelerator, the ISR and the SppS at CERN, the Tevatron collider at FNAL allowed to learn the hadron interaction properties at high energies. The accelerator experiments together with theoretical efforts resulted in the construction of the “Standard Model” with clear understanding and power predictions at least in the electro-weak sector and with a number of new open questions. It is believed that new collider experiments such as the LHC project at CERN and others might help to find the answers to the open questions in Particle Physics. At the same time it is quite clear that the new measurements at the accelerator experiments would be of great importance for Cosmic Rays Physics. This is because high energy cosmic rays are usually measured indirectly by investigating the air showers they produce in the atmosphere of the earth. A correct interpretation of the air shower measurements with a necessity requires an improved understanding of the hadron interaction properties, explored by the accelerator experiments. There is a clear necessity to measure at accelerators the global characteristics of the high energy hadron interactions with a high accuracy.

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in order to accurately interpret the existing and newly data on the measurements of the highest energy air showers. Certainly, this request, addressed to the physicists working on the hadron accelerators, is clearly and strongly motivated.

The progress in Cosmic Rays Physics during “accelerator era” has been less substantial compared to Particle Physics. Probably the main reason of that is owing to above mentioned divergence between two branches in fundamental science. However, the recent results in cosmic ray studies and new astrophysical observations open a new page in Particle Physics. One of the most interesting results is the detection of cosmic ray particles with energies exceeded $10^{19}$ eV. Ref. [1] is the first article where the detection of a cosmic ray with energy $10^{20}$ eV has been published (the Volcano Ranch experiment). At present time the total number of detected air showers with energy higher than $10^{20}$ eV is about 20 [2]. The existence of cosmic ray particles with energies above $10^{20}$ eV has been confirmed by all experiments, regardless of the experimental technique used [2]. Why this result is so interesting for Particle Physics?

It is well known that soon after the discovery of the Cosmic Microwave Background Radiation (CMBR) by Penzias and Wilson [3] almost simultaneously Greisen in the USA [4] and Zatsepin&Kuzmin [5] in the USSR predicted that above $10^{20}$ eV the cosmic ray spectrum will steepen abruptly (GZK effect). The cause of that catastrophic cutoff is the intense isotropic CMBR which is really a 2.7K thermal blackbody radiation produced at a very early stage of the Universe evolution and confirmed by measurements of Roll and Wilkinson [6]. CMBR photons with a 2.7K thermal spectrum fill the whole Universe with a number density of $\sim 400$ cm$^{-3}$. The physical mechanism of the GZK cutoff is quite clear, it is based on the interactions of Ultra-High Energy Cosmic Ray (UHECR) particles with CMBR photons. Protons, photons, electrons, neutrinos, nuclei etc might be as such UHECR particles. Mainly the process that cause the energy loss of UHECR particle, say proton, is the photo-production of pions on CMBR photons: $p + \gamma_{\text{cmb}} \rightarrow p + \pi$. The threshold center of mass energy for photoproduction of one pion is $\sqrt{s}_{\text{thr}} = m_p + m_{\pi^0} \simeq 1073$ MeV. In the Cosmic Rest Frame (CRF, defined as the frame in which the CMBR is represented as isotropic photon gas) one can estimate the proton threshold energy for pion photoproduction

$$E_{p, \text{thr}}^\text{CRF} = \frac{s_{\text{thr}} - m_p^2}{2\varepsilon_{\text{cmb}}} = \frac{m_{\pi}(m_p + m_{\pi^0}/2)}{\varepsilon_{\text{cmb}}} \simeq 13.6 \times 10^{16} \left(\frac{\varepsilon_{\text{cmb}}}{\text{eV}}\right)^{-1} \text{eV},$$

where $E_{p, \text{thr}}^\text{CRF}$ is the proton energy in the Cosmic Rest Frame. Taking the average energy $\varepsilon_{\text{cmb}} = 6.3 \times 10^{-4}$ eV, the proton threshold energy is $E_{p, \text{thr}}^\text{CRF} \simeq 2.15 \times 10^{20}$ eV.

On the other hand, in the rest frame of a cosmic ray proton (PRF – projectile rest frame) a substantial fraction of the CMBR photons will look as $\gamma$-rays with energy above the threshold energy for pion photoproduction

$$\varepsilon_{\gamma_{\text{cmb}}, \text{thr}}^\text{PRF} = \frac{s_{\text{thr}} - m_p^2}{2m_p} = m_{\pi} + \frac{m_{\pi^0}}{2m_p} \simeq 145 \text{MeV},$$

where $\varepsilon_{\gamma_{\text{cmb}}, \text{thr}}^\text{PRF}$ is the CMBR photon energy in the projectile rest frame. The photoproduction cross section as a function of projectile photons for stationary protons is very well measured and studied at accelerator experiments [7]. There is a detail information that is shown in Fig. 1. At low energies the cross section exhibits a pronounced

\footnote{See, however, recent article [32].}
resonance associated with the $\Delta^+$ decaying into $p\pi^0$ mode; here the cross section exceeds 500 $\mu$b at the peak. The complicated range beyond the $\Delta^+$-resonance is essentially dominated by the higher mass resonances associated with multiple pion production $\gamma + p \rightarrow \Delta^* \rightarrow p + n\pi, n > 1$. The whole resonance range is followed by the long tail with approximately constant cross section about 100 $\mu$b with a slow increase up to 1 TeV. The photo-pion production cross section for neutrons is to a good approximation identical. As seen from Fig. 1 at half-width of the $\Delta^+$ resonance peak the total cross section $\sigma_{sp} \simeq 300$ $\mu$b $= 3 \times 10^{-28}$ cm$^2$. Taking into account the number density of the CMBR photons $n_{\gamma,cmb} \sim 400$ cm$^{-3}$, for the mean free path $l$ in the CMBR photon gas one obtains

$$l = \frac{1}{n\sigma} \simeq 8.3 \times 10^4 \text{cm} \simeq 2.8 \text{Mpc}. \quad (3)$$

The next important parameter is the proton inelasticity $k_{inel}$ defining the fraction of energy that a proton loses in one collision. At threshold in each collision protons lose about 18% of their energy, and this energy loss fraction increases with increase of energy. In that way the energy loss length $L = l/k_{inel}$ is estimated about a few tens Mpc for protons with energy higher than $10^{20}$ eV.

Apart from photo-pion production, the process of pair production $p + \gamma_{cmb} \rightarrow p + e^+e^-$ should be considered as well. While this process has a smaller threshold by a factor $2m_e/m_\pi$, it has a smaller cross section. Thus, the estimated energy loss length $L$ is about $10^3$ Mpc. Nevertheless, this process might be important at sub–GZK energies. The detailed analysis of the energy loss length of protons in interactions with the CMBR photons is presented in Fig. 2.

For neutrons with $E \sim 10^{20}$ eV, the dominant loss process is $\beta$–decay $n \rightarrow p + e^+\bar{\nu}_e$. The neutron decay rate $\Gamma_n = m_n/E\tau_n$, with the laboratory lifetime $\tau_n \simeq 888.6$ sec, gives the neutron energy loss length

$$L_n = \tau_n E m_n \simeq 0.9 \left( \frac{E}{10^{20}\text{eV}} \right) \text{Mpc}. \quad (4)$$

Obviously, UHECRs nuclei are expose to the same energy loss processes as UHECRs protons. So that, the respective threshold for the photo-pion production reaction, in particular, $A + \gamma_{cmb} \rightarrow A + \pi^0$, is given by change of $m_p$ with the mass of the nucleus in Eq. 1

$$E_{\text{CRF}}^{A,\text{thr}} = \frac{m_{A}(m_A + m_\pi/2)}{\varepsilon_{\gamma,cmb}} \simeq AE_{p,\text{thr}}^{\text{CRF}}. \quad (5)$$

From Eq. 5 it follows that the GZK cutoff energy for nuclei is shifted to larger values for heavier nuclei. However, it turns out that the dominant energy loss process for nuclei is photodisintegration, typically $A + \gamma_{cmb} \rightarrow (A - 1) + N, (A - 2) + 2N, \ldots$, happening due to giant resonances at about the same primary energy. In fact, here we have another excellent example of intersection between nuclear&particle physics and high-energy cosmic rays physics. Recent detailed studies reveal that photodisintegration for nuclei leads to energy loss length of $\sim 10$ Mpc at energy $2 \times 10^{20}$ eV, which is comparable with the energy loss length for nucleons.

Well, to resume the GZK effect physically means that isotropic CMBR photon gas makes the Universe opaque to UHECRs particles whose energy is greater than $10^{20}$ eV. In terms of the energy loss length the GZK cutoff looks like a suppression of the UHECRs
flux due to restriction of the propagation distance to a few tens of Mpc. In that sense a notion of the GZK sphere arises: simply it is a sphere with the radius $R_{GZK} \approx 50$ Mpc within which a source has to locate to be the origin of the UHECRs particles with energy $\gtrsim 10^{20}$ eV.

As mentioned above the cosmic ray particles with energies exceeded $10^{20}$ eV have been detected. The data on the UHECRs spectra measured by Fly’s Eye, AGASA, HiRes I, and HiRes II Collaborations are collected and shown in Fig. 3, extracted from Ref. [9] (see references therein). As seen from Fig. 3 the combined UHECR spectrum does not exhibit the GZK cutoff at all, many events with $E > 10^{20}$ eV have been observed. The strongest evidence for trans-GZK events comes from the AGASA observations. The AGASA group reported the detection of up to 17 events with energy $\gtrsim 10^{20}$ eV and claimed that GZK cutoff effect is not observed. Now a non-observation of the GZK effect is known as the GZK puzzle. Of course, the GZK puzzle results in uncommonly profound consequences, raising questions to the nature of the primary UHECRs particles and their sources as well as the physical mechanisms responsible for endowing cosmic ray particles with such enormous energies or even to the particle physics in itself. That’s why the GZK puzzle and all around of that are the targets of wide discussions in the literature at present time. Many ideas and different models as solutions have been suggested [10], however, the true solution of the GZK puzzle is unknown so far.

Looking at Figure 3, one can see that the UHECR spectrum exhibits a dip structure at the energy about $10^{20}$ eV, i.e. the spectrum really has a minimum just at the GZK cutoff energy. Thus the GZK puzzle (irrespective of the source and accelerating mechanism for cosmic rays particles) is transformed into the questions: what is the origin of this minimum, and how could one explain an appearance of the minimum in the UHECR spectrum in the framework of fundamental dynamics in particle physics. Here we suggest a conjecture that the minimum in the UHECR spectrum might be related with nontrivial structure of the inelastic defect of total cross sections in scattering from nuclei. This point will be discussed in a more detail below.

## 2 On Total Cross Sections in Scattering from Nuclei

In the middle of XX century experimental and theoretical studies of high-energy particle interaction with deuterons have shown that even in the range of asymptotically high energies the total cross section in scattering from deuteron cannot be treated as a simple sum of the proton and neutron total cross sections. Glauber was the first to explain why a simple addition of the elementary free nucleon cross sections might be failed. Using the methods of diffraction theory, the quasiclassical picture for scattering from composite systems and eikonal approximation for high-energy scattering amplitudes, he found fifty years ago [11] that the deuteron total cross section can be expressed by the formula

$$\sigma_d = \sigma_p + \sigma_n - \delta\sigma_d,$$

where

$$\delta\sigma_d = \delta\sigma_d^G = \frac{\sigma_p \cdot \sigma_n}{4\pi} < \frac{1}{r^2} >_d.$$

Here $\sigma_d, \sigma_p, \sigma_n$ are the total cross sections in scattering from deuteron, proton and neutron, $< r^{-2} >_d$ is the average value for the inverse square of the distance between the nucleons.
inside a deuteron, $\delta \sigma_d^G$ is the Glauber shadow correction describing the effect of eclipsing or the screening effect in the recent terminology. The Glauber shadow correction has quite a clear physical interpretation. This correction originates from elastic rescattering of an incident particle on the nucleons in a deuteron and corresponds to the configuration when the relative position of the nucleons in a deuteron is such that one casts its “shadow” on the other. It is a genuine analog of the effect known for astronomers; the decrease in luminosity of binary star systems during eclipses [11].

Soon after it was understood that in the range of high energies the shadow effects may arise due to inelastic interactions of an incident particle with the nucleons of a deuteron. Therefore, an inelastic shadow correction had to be added to the Glauber one. A simple formula for the total (elastic plus inelastic) shadow correction had been derived by Gribov [12] in the assumption of Pomeron dominance in the dynamics of elastic and inelastic interactions

$$\delta \sigma_d^\Gamma = 2 \int d\mathbf{q}^2 \rho(4\mathbf{q}^2) \frac{d\sigma_N}{d\mathbf{q}^2},$$

where $\rho(\mathbf{q}^2)$ is the deuteron (charge) formfactor, $d\sigma_N/d\mathbf{q}^2$ is the sum of cross sections of all processes which take place in interaction of incident hadron with the nucleon at fixed transfer momentum $\mathbf{q}^2$. However, it was observed later on that the calculations performed by the Gribov formula did not meet the experimental data: The calculated values of the shadow correction overestimated the experimental measurements. In that case the idea, that the Pomeron dominance is not justified at the accelerator energies, becomes clear.

It was believed sometime that the account of the triple-reggeon diagrams for six-point amplitude in addition to the triple-pomeron ones would allow to obtain a good agreement with the experiment. But careful analysis has shown that discrepancy between theory and experiment could not be eliminated by taking into account the triple-reggeon diagrams: In fact, it is needed to modify the dynamics of the six-point amplitude with more complicated diagrams than the triple Regge ones [13]. This indicates that up to now there is no a clear understanding, in the framework of Regge phenomenology, the shadow corrections in elastic scattering from deuteron.

The main difficulty, which the Regge phenomenology faced with, was the problem to describe the cross section of the single diffraction dissociation processes. The latest experimental measurement of $pp$ single diffraction dissociation at c.m.s. energies $\sqrt{s} = 546$ and $1800$ GeV, carried out by the CDF group at the Fermilab Tevatron collider [14], has shown that the most popular model of supercritical Pomeron does not describe the existing experimental data. Recent experimental results from HERA [15] lead us to the same conclusion. The soft Pomeron phenomenology as currently developed cannot incorporate the HERA data on structure function $F_2$ at small $x$ and total $\gamma^*p$ cross section from $F_2$ measurements as a function of $W^2$ for different $Q^2$. Such situation might be qualified as a “super-crisis” for the supercritical Pomeron model. Figure 1 extracted from paper [16] demonstrates the “super-crisis” (see details in Ref. [18]).

Meanwhile it’s quite clear that the theoretical understanding of the shielding effects in scattering from any composite system is of fundamental importance, because the structure of shadow corrections is deeply related to the structure of the composite system itself. At the same time the structure of the shadow corrections displays new aspects for the fundamental dynamics.

In the second half of 1970th we have concerned in the study of dynamics in three particles scattering in some details (see recent review article [19] and references therein).
The Bethe-Salpeter-type equations reduced to one time have been used as an implement in our study of a dynamics for the three-body systems. It turned out that the three-body dynamics, under a consistent consideration of three-body problem in the framework of local quantum field theory, with a necessity contained new fundamental forces which the three-body forces are. The three-body forces in relativistic quantum theory appear as an inherent connected part of total three particle interaction which cannot be represented by the sum of pair interactions. An existence of the three-body forces might be established even in the perturbation theory expansions. Single-time formalism in Quantum Field Theory used allows one to give a constructive definition of the three-body forces beyond the perturbation theory. On this way it was established that the fundamental three-body forces are related with specific inelastic interactions in two-body subsystems of the three-body system, and they govern the dynamics of special inelastic processes known as one-particle inclusive reactions. At the rather common assumptions we managed to calculate the contribution of the three-body forces to the deuteron total cross section and to derive the new, extremely simple and refined formula for defect of total cross section in scattering from deuteron with clear and transparent physical interpretation. The obtained structure of the shadow corrections to the deuteron total cross section has revealed new fundamental scaling laws \cite{20} in interaction of composite nuclear systems. Here I would like to concern this point in a more detail.

In our approach the defect of the deuteron total cross section is represented by the sum of two items

\[ \delta \sigma_d = \delta \sigma_d^{el} + \delta \sigma_d^{inel}, \]  

where \( \delta \sigma_d^{el} \) is elastic defect, and \( \delta \sigma_d^{inel} \) is inelastic one. For the elastic and inelastic defects one obtains

\[ \begin{align*}
\delta \sigma_d^{el} &= 2 a_d^{el} (x_{el}^2) \sigma_{el}^N, \\
\delta \sigma_d^{inel} &= 2 a_d^{inel} (x_{inel}^2) \sigma_{sd}^N,
\end{align*} \]  

where

\[ \begin{align*}
x_{el}^2 &= \frac{2 B_{el}^N}{R_d^2} = \left( \frac{R_{eff}^2}{R_d^2} \right)^2, \\
x_{inel}^2 &= \frac{2 B_{sd}^N}{R_d^2} = \left( \frac{R_{eff}^3}{R_d^2} \right)^2.
\]  

As seen from Eq. (10) the elastic defect is proportional to the total elastic cross section, but the inelastic defect is proportional to the total single diffraction dissociation cross section in scattering from nucleon. The proportionality factors \( a_d^{el} \) and \( a_d^{inel} \) are called the elastic and inelastic structure functions of a deuteron correspondingly. Here \( R_d \) is the deuteron radius defined by the deuteron formfactor, and scale variables \( x_{el} \) and \( x_{inel} \) are defined through the slope of forward diffraction cone in elastic scattering \( B_{el}^N \) and in single diffraction dissociation \( B_{sd}^N \) which are simply related to the effective radii of two-body \( B_{el}^N = (R_{eff}^2)^2 / 2 \) and three-body \( B_{sd}^N = (R_{eff}^3)^2 / 2 \) forces. Of course, it is supposed, that both at elastic and at inelastic interactions with nucleons of a deuteron, proton and neutron are dynamically indistinguishable, i.e. appropriate dynamic characteristics for a proton and neutron are identical \( \sigma_{el}^p = \sigma_{el}^n = \sigma_{el}^N, B_{el}^p = B_{el}^n = B_{el}^N \) etc. Such assumption is quite justified at enough high energies.

Structure functions have clear and quite a transparent physical meaning. The function \( a_{el} \) is some kind of “counter”, which measures out a portion of events related with elastic rescattering of incident hadron on nucleons of a deuteron among of all the events during the interaction with a deuteron as whole, and this function attached to the total probability of elastic interaction of an incident particle with a separate nucleon in a deuteron. This function depends on a variable, which is effective radius of elastic interaction with a
nucleon measured with the help of “scale rule” with a scale defined by the radius of a deuteron. At each value of this variable (at a given value of energy) the number of the function \(a_{el}\) determines a weight, which the total cross section of elastic interaction with a nucleon at given energy enters the defect of the deuteron total cross section with.

The same physical interpretation with obvious changes in the terms is transferred on the inelastic structure function. The function \(a_{inel}\) also represents some kind of “instrument”, but another, which count out a relative portion of other events among of possible interactions with a deuteron as a whole related with processes of inelastic interaction with nucleons inside a deuteron of inclusive type in the region of diffraction dissociation. The inelastic structure function depends on another scale variable, which is effective radius of inelastic interaction with a nucleon measured with the help of “scale rule” with the same scale defined by the radius of a deuteron. The number of the function \(a_{inel}\) at given value of energy determines a weight, which the total single diffraction dissociation cross section on a nucleon at the same energy enters the defect of the deuteron total cross section with.

Formulas (9) and (10) may serve as toolkit for experimental study of structure functions \(a_{el}\) and \(a_{inel}\) by measurement of the defect for total cross section in scattering from deuteron with usage of the experimental information about elastic cross section and total cross section of single diffraction dissociation on a nucleon. For these purposes, however, it would be extremely important to have a reliable substantiation of these formulas. It is remarkable that such theoretical substantiation can be really obtained.

The formalism, which we have used, allowed us to carry out analytical calculations completely, if for these purposes to take advantage of the parameterizations, trustworthy established on experiment, for differential elastic cross sections and for one-particle inclusive cross sections in the range of diffraction dissociation

\[
\frac{d\sigma_{el}^d}{dt}(s, t) = \frac{d\sigma_{N}^d}{dt}(s, 0) \exp[B_{N}(s)t], \quad \frac{2s}{\pi} \frac{d\sigma_{el}^d}{dtdM^2} = A(s, M^2_\chi) \exp[b(s, M^2_\chi)t]. \quad (11)
\]

In this way we managed to get the extremely simple formulas for structure functions \(a_{el}^d\) and \(a_{inel}^d\), which look like

\[
a_{el}^d(x^2) = \frac{x^2}{1 + x^2}, \quad a_{inel}^d(x^2) = \frac{x^2}{(1 + x^2)^2}. \quad (12)
\]

It should be especially emphasized once more an important element in our approach which consists that the inelastic defect in the deuteron total cross section appears as manifestation of the fundamental three-body forces, and at the same the three-body forces determine the dynamics of one-particle inclusive reactions. Formula relating the three-body forces amplitude with the one-particle inclusive cross section has been derived as well; see details in Refs. [19, 20, 21] and references therein.

Outcome of functions evaluations (12) and analysis of these functions, however, are worthy of separate discussion. At first, being returned to the formula (9), we shall remark that the Glauber formula is followed if in this formula to neglect inelastic defect and for the elastic structure function to take approximation \(a_{el}^d(x^2) \approx x^2\) justified at \(x^2 \ll 1\), and to take into account that \(\sigma_{el}^d \approx \sigma_{el}^{tot}/16\pi B_{el}^d\). Secondly, it is necessary to pay attention that the structure functions \(a_{el}^d\) and \(a_{inel}^d\) have quite different behavior: \(a_{el}^d(x^2)\) is the monotonic (increasing) function when argument vary on a semi-infinite interval \(0 \leq x^2 < \infty\), and the range of its values is limited to an interval \(0 \leq a_{el}^d < 1\), while the function \(a_{inel}^d\)
at first increases, reaches a maximum at $x^2 = 2$, and then decreases, disappearing at infinity, thus the range of its values is an interval $0 \leq a_{d}^{inel} \leq 2/3\sqrt{3}$. Certainly, that such distinction in behavior of structure functions $a_{d}^{el}$ and $a_{d}^{inel}$ results in far-reaching physical corollaries. For example, at superhigh energies corresponding $x^2 \to \infty$, we discover the effect of weakening the inelastic screening i.e. the inelastic defect disappears (taking into account that $\sigma^{sd}_{N} < \text{Const}, s \to \infty$), the elastic defect tends to doubled value of the nucleon total elastic cross section, and the deuteron total cross section comes nearer to doubled value of the nucleon total absorption cross section. Therefore, at superhigh energies the $A$–dependence of the total cross sections in scattering from nuclei should be recovered with that only by odds that the fundamental value, standing at $A$, is not the nucleon total cross section but the nucleon total absorption one. This means that the total absorption (inelastic) cross section manifests itself as a fundamental dynamical quantity for the constituents in a composite system at superhigh energies.

Of course, without any doubt, matching of the obtained theoretical outcomes with available experimental data on total cross sections in scattering of protons and antiprotons from deuterons represented for us the special interest. In figures 5 and 6 the preliminary results of such matching are shown. The curves in these figures correspond to the total cross sections in scattering of protons and antiprotons from deuterons calculated by the formulas [6,9,10,12]. There the global descriptions of $pp$ and $\bar{p}p$ total cross sections (see Figs. 7,8) as well as of total single diffraction dissociation cross section in view of the latest experimental data obtained by CDF Collaboration at FNAL [14], made by us earlier [18], have been used.

Besides in the given occasion it should be necessary still to emphasize, that the matching with experimental data on total cross sections in scattering of protons and antiprotons from deuterons was carried out, as it were, in two stages. At the first stage the theoretical calculations were compared to experimental data on the antiproton-deuteron total cross section on the supposition, that $R_{d}^{2}$ is the single free parameter, which value should be determined from the fit to experimental data. As a result of a statistical analysis the following value for the $R_{d}^{2}$ was obtained: $R_{d}^{2} = 66.61 \pm 1.16 \text{GeV}^{-2}$. Here pertinently to pay attention to the following circumstance. The last experimental measurements of the deuteron matter radius testify $r_{d,m} = 1.963(4) \text{fm}$ [22] whence follows that $r_{d,m}^{2} = 3.853 \text{fm}^{2} = 98.96 \text{GeV}^{-2}$. The obtained value for $R_{d}^{2}$ satisfies equation $R_{d}^{2} = 2/3 r_{d,m}^{2}$. For entirety, the outcomes of theoretical calculations are represented in Fig. 7 up to energies of Tevatron at FNAL. At the second stage the experimental data on the proton-deuteron total cross section were compared to theoretical calculations, in which the value of $R_{d}^{2}$ was fixed on the numerical value, which was obtained at the first stage from the analysis of the data on $\bar{p}d$ total cross section. In other words, the curve in Fig. 8 corresponds to theoretical calculations made with the help of the formulas [6,9,10,12], in which there was no free parameter. In this figure the outcomes of theoretical calculations are also represented up to energies of Tevatron at FNAL. As is seen, the figures 7 and 8 testify to the excellent agreement between the theory and experiment. In addition Figures 9 and 10 demonstrate our global description of the proton-proton total cross section from the most low energies up to energies reachable in cosmic rays.

In Figure 11 the outcomes of the theoretical calculations of elastic and inelastic defects of total cross section in scattering of (anti)protons from deuterons in energy range $\sqrt{s} \sim 10 \div 2000 \text{ GeV}$ have been depicted. It follows from these calculations that the value of elastic defect makes about 10% from the value of nucleon–nucleon total cross section,
and the value of inelastic defect makes about 10% from the value of elastic defect i.e. approximately 1% from the value of nucleon–nucleon total cross section. Figuratively expressing, it would be possible to tell that if the elastic defect represents a fine structure of total cross section in scattering from deuteron then the inelastic defect should be referred to a hyperfine one.

In our approach the inelastic defect is related to manifestation of fundamental three-body forces, therefore in this sense the three-body forces play a role of “fine tuning” in the dynamics of the relativistic three-particle system. It is necessary to render homage to the physicists-experimenters creating setups with the accuracy of measurements permitting to discriminate inelastic defects in total cross sections of particles scattering at high energies. In this connection the further experimental precise measurements of the hadron–deuteron total cross sections at high energies seem to be extremely important.

As it was already mentioned above the maximum value of inelastic defect is achieved at \((x_{inel}^d)^2 = 2 (s_{max}/R_d^2)\). Or else, the value of energy corresponding to maximum value of the inelastic defect is defined from the equation \(R_3^2(s_{max}) = 2 R_d^2\). The calculations made in view of our analysis of existing experimental data give \(\sqrt{s_{max}} = 9.01 \times 10^8\) GeV = 9.01 \times 10^{17}\) eV. Reevaluating c.m. energy \(\sqrt{s_{max}}\) to the lab. system one obtains \(E_{max}^{lab} \simeq s_{max}/(2m_p) = 4.8 \times 10^{25}\) eV. It is obvious, that such values of energies are not accessible on current and design accelerators. However it would be extremely interesting to look for manifestations of the given effect in phenomena related with extremely high energy cosmic rays.

3 Discussion

The theoretically calculated inelastic defect in the region of a maximum is shown in Figure 12. As it follows from Eq. (6) a maximum of the inelastic defect corresponds to a minimum of the total cross section. We have plotted in Figure 13 the (anti)proton–deuteron total cross section scaled by the factor \(\ln^{3/2}(\sqrt{s}/s_0)\) in the region of a maximum of the inelastic defect. The scale factor is selected \(ad\ arbitrium\) for a goal of illustration only to discern a minimum in the total cross section.

Let’s remark, however, that the value \(s_{max}\) has clear physical meaning, it separates two ranges on energy: the range of energies \(s < s_{max}\), at which effective radius of three-body forces does not exceed size of a deuteron or more exactly \(R_3^2(s)/2 < R_d^2\), and the range of energies \(s > s_{max}\), at which effective radius of three-body forces becomes more than size of a deuteron \(R_3^2(s)/2 > R_d^2\). The existence of boundary \(s_{max}\), since which there is a suppression of inelastic defect, seems to be the extremely important characteristic of fundamental dynamics.

Here we would like to make a conjecture that the observed structures in the cosmic rays spectra, in particular a minimum in the UHECR spectrum, might be related with the existence of such boundary.

From the Glauber formula (7) it follows, that with decrease of inter-nucleon distance in a deuteron the value of elastic defect grows. But the configurations with small inter-nucleon distances in a deuteron are most favorable for a manifestation of purely three-particle interaction. When effective interaction radius of an incident hadron with a nucleon becomes comparable with inter-nucleon distance, the pattern of elastic rescattering on nucleons of a deuteron ceases to be adequate to complete pattern of interaction with a
deuteron. In this case it is also necessary to take into account purely three-particle forces. It is obvious, that in a deuteron the configurations are dynamically probable, when the nucleons are close from each other, but the Glauber theory does not allow to take into account such configurations. Account of such configurations demands a more detailed study of the dynamics of processes of scattering from a deuteron. The technique of the dynamic equations in a quantum field theory, which we have used, just allows to carry out such detailed investigations. Once again it should be emphasized, that the important role in our researches was assigned to conceptual notion of fundamental three-body forces which with necessity arise by consistent consideration of the dynamics of three particles system within the framework of a relativistic quantum theory. The relation of fundamental three-body forces with dynamics of one-particle inclusive reactions represents the important outcome obtained, as it were, by the way. This outcome especially is important, that can form the basis both for elaboration of methods of analytical calculations and for a different sort of phenomenological analysis.

The comparison of the theory with experimental data on (anti)proton–deuteron total cross sections made shows, that for the description of particles scattering from a deuteron at high energies it is enough to take into account only nucleon degrees of freedom in a deuteron. The weakly bounded two-nucleon system the deuteron looks so, that the clustering of quarks in nucleons is not broken even then, when the nucleons approach closely to each other. Nucleons, being close from each other in a deuteron, do not lose of the individuality and consequently there is no necessity to introduce the six-quark configurations depersonalized in a deuteron. The structure derived for the defect of total cross section in scattering from a deuteron corresponds to such pattern.

We managed to show, that the general formalism of quantum field theory admits a possibility of representation of dynamics of a particle scattering from composite system through the fundamental dynamics of a particle scattering from isolated constituents and structure of the composite system itself. Though the dynamics of a particle scattering from two-particle bound system a deuteron was considered in details, the general formalism used admits a natural generalization and extension to more complex multiparticle compound nuclear systems. Certainly, the complexity of consideration, at that, substantially increases.

Really, to consider the problem of scattering from nucleus consisting of \( A \) nucleons we have to solve many-body problem for \((A+1)\)–particle system. However, instead of solving this very complicated problem one could use a powerful reduction method. For this goal let’s consider a nucleus consisting of \( A \) nucleons as a bound system of one nucleon and nucleus consisting of \((A – 1)\) nucleons. In that case the problem of scattering from a nucleus with \( A \) nucleons is reduced to the problem of scattering from a two-body bound system which has been previously solved. Of course such supposition is not unique and should be considered as a some sort of simplification. In the other way one could suppose that a nucleus consisting of \( A \) nucleons may be represented as a two-body bound system of a nucleus with \( A_1 \) nucleons and other nucleus with \( A_2 \) nucleons so that \( A_1 + A_2 = A \). By this way the problem of scattering from a nucleus with \( A \) nucleons is also reduced to the problem of scattering from a “deuteron” previously solved. Anyway continuing a reduction in both cases we will come at a final stage to the expression for total cross section in scattering from a nucleus in terms of fundamental dynamics in scattering from a nucleon and the structure of a nucleus.

Formula (6) for total cross section in a case of scattering from any nucleus with \( A \)
nucleons can be rewritten in the form

\[ \sigma_A = A\sigma_N - \delta\sigma_A, \]  

(13)

where \( \sigma_N \) is the total cross sections in scattering from nucleon. The defect \( \delta\sigma_A \), in general, also contains two parts as in Eq. (9)

\[ \delta\sigma_A = \delta\sigma_{el}^A + \delta\sigma_{inel}^A, \]  

(14)

where \( \delta\sigma_{el}^A \) is elastic defect, and \( \delta\sigma_{inel}^A \) is inelastic one. From general point of view, as presented above, for the elastic and inelastic defects one can write

\[ \delta\sigma_{el}^A = a_{el}^A(X_{el}^2)\sigma_{el}^N, \quad \delta\sigma_{inel}^A = a_{inel}^A(X_{inel}^2)\sigma_{sd}^N, \]  

(15)

where

\[ X_{el}^2 = \frac{2 B_{el}^N}{R_A^2} = \left(\frac{R_{eff}^2}{R_A^2}\right)^2, \quad X_{inel}^2 = \frac{2 B_{sd}^N}{R_A^2} = \left(\frac{R_{eff}^3}{R_A^2}\right)^2. \]

The functions \( a_{el}^A \) and \( a_{inel}^A \) are called the elastic and inelastic structure functions of a nucleus. Here we have included the combinatorial factors in the definition of the structure functions. \( R_A \) is the nucleus radius defined by the nucleus formfactor. The scaled variables \( X_{el} \) and \( X_{inel} \) are defined as \( x_{el} \) and \( x_{inel} \) above but with another scale factor \( R_A \) which is the radius of a nucleus as it should be. It is obviously that formulas (14) and (15) may serve as a base to experimentally study the structure functions \( a_{el}^A \) and \( a_{inel}^A \) by measuring the defect of total cross section in scattering from nuclei with using the experimental information about elastic cross section and total cross section of single diffraction dissociation in scattering from a nucleon. To calculate the structure functions \( a_{el}^A \) and \( a_{inel}^A \) is a task of any theory or theoretical model. As mentioned above the calculation of the structure functions \( a_{el}^A \) and \( a_{inel}^A \) in quantum field theory is a very complicated problem. However, it would reasonably to use our experience acquired in solution of this problem for deuteron case.

Really, it seems to a good approximation, one could use the following expressions for the structure functions \( a_{el}^A \) and \( a_{inel}^A \) of any nucleus

\[ a_{el}^A(X^2) = A \frac{X^2}{1 + X^2}, \quad a_{inel}^A(X^2) = A \frac{X^2}{(1 + X^2)^{3/2}}. \]  

(16)

Here we have applied the identity

\[ \sum_{k=2}^A (-1)^k k \binom{A}{k} = A, \]  

(17)

and supposed that any many-fold rescattering in a nucleus feels one and the same structure function like for two-fold rescattering. It is clear that this supposition is a strong enough simplification, however, it might be precise one at ultra-high energies. At any rate, it would be very desired to test such simple pattern in ultra-high energy cosmic rays.

For the effective radius of three-nucleon forces obtained in our previous investigations one can write the following analytical expression

\[ R_{3}^2(s) = \left[ 5.2667 + 0.4137 \ln^2(\frac{s}{s_0})^{1/2} \right] \text{GeV}^{-2}, \quad (s_0)^{1/2} = 20.74 \text{GeV}. \]  

(18)
Then the equation $R^2\left(s_{\text{max}}\right) = 2R^2_A$, defining a value of energy at a maximum of the inelastic defect, has an obvious solution

\[
(s_{\text{max}})^{1/2} = (s_0)^{1/2} \exp \left[ \frac{2R^2_A - 5.2667}{0.4137} \right]^{1/2}.
\]  

(19)

Further, if we put as $R_A = r_0 A^{1/3} = R_d(A/2)^{1/3}$, then Eq. (19) can be rewritten in the form

\[
(s_{\text{max}})^{1/2} = 20.74 \exp \left[ \frac{133.22(A/2)^{2/3} - 5.2667}{0.4137} \right]^{1/2} \text{ GeV},
\]  

(20)

where the value for the deuteron radius $R^2_d = 66.61 \text{ GeV}^{-2}$ mentioned above has been used. From Eq. (20) one obtains

\[(s_{\text{max}})_{A=2}^{1/2} = 9.01 \times 10^8 \text{ GeV}, \quad (s_{\text{max}})_{A=3}^{1/2} = 1.27 \times 10^{10} \text{ GeV}, \quad (s_{\text{max}})_{A=4}^{1/2} = 1.03 \times 10^{11} \text{ GeV}, \ldots\]

Here, it is interesting to note that the GZK cutoff value $\sim 10^{11} \text{ GeV}$ appears for c.m. energy corresponding to maximum of the inelastic defect in a case of scattering from Helium nucleus.

The $A$-dependence in position of a maximum of the inelastic defect in scattering from nuclei may have a direct link to the question on chemical composition of the cosmic rays. An information about chemical composition of the cosmic rays can be elicited from detailed study of air showers development. It is quite clear, for instance, that air showers produced by heavy nuclei start the development in the earth atmosphere earlier compared to protons as primaries. The cosmic rays composition is often investigated by fitting the energy dependence of the depth into the atmosphere of maximum $X_{\text{max}}$ of the UHECRs-generated air showers. In fact, $X_{\text{max}}$ is the atmospheric depth at which the number of particles in a shower reaches its maximum. This quantity strongly depends on the primary energy and composition, that’s why $X_{\text{max}}$ if often considered as the most useful observable of the air showers. At ground array detectors $X_{\text{max}}$ is mainly provided by measuring the muon content or more exactly the ratio of electrons to muons in air shower. In other case, optical fluorescent detectors allow to directly observe air shower development. Just to say qualitatively, it should be mentioned that for a given primary energy a heavier nucleus creates air shower with a higher muon content and $<X_{\text{max}}>$ is higher up in the atmosphere compared to those for a proton-generated air shower. The higher muon content of air shower produced by heavy nucleus can be understood by the fact that it is relatively easier for charge pions to decay to muons before interacting with the medium when the shower develops higher up in the less dense atmosphere. Besides, a less energetic pions generated from heavy nucleus have a higher decay probability, therefore the muon fraction is higher in air showers produced by heavy nuclei as well by this reason. This is clearly demonstrated in Fig. 14 where the results of the Kascade air shower experiment have been fitted, using the QGSJET model generator, with a composition dominated by Helium nuclei and smaller contributions of proton, $^{16}\text{O}$ and $^{56}\text{Fe}$.

As can be seen from Figure 15, the iron fraction gradually decreases when changing the energy from $10^{17}$ to $10^{20} \text{ eV}$, but the fraction of lighter nuclei increases in the same interval of energies i.e. there is trend from heavy toward lighter composition in the measurements of $<X_{\text{max}}>$. It seems, the recent studies indicate that at the highest energies $\gtrsim 10^{19} \text{ eV}$ there is a significant fraction of nuclei with charge greater than unity, and less than 50%
of the primary cosmic rays can be photons. In another words, the existing experimental
data suggest that UHECRs are predominantly protons or light nuclei as for cosmic rays at
much lower energies. However, due to poor statistics and large fluctuations from shower
to shower the definite conclusions on the composition of the UHECRs have to await data
from next generation experiments.

Here, we would like to emphasize that the simulation of shower development depends
on the event generator used containing some model of hadronic interaction which results in
further complication of data interpretation. The major uncertainties in air shower simula-
tion stem from the hadronic interaction models which are usually represented by empirical
parameterizations, and therefore almost all hadronic models are purely phenomenological.
This is because one cannot calculate soft hadronic interaction cross sections or hadronic
multiparticle production within QCD from first principles. The second major source of
uncertainty is the large extrapolation (over 6 orders of magnitude in energy) from accel-
erator experimental data to the UHECRs ones. In this place the reliable model and the
precise accelerator data on fundamental, for example hadron-proton, total cross sections
as well as on total cross sections in scattering from nuclei are needed to constrain un-
certainties in the interpretation of cosmic rays data to accurately determine the energy
spectrum and the composition of the UHECRs. Additionally, theoretical understanding
and description of the diffractive dissociation processes are of special importance for nuclei
interactions and consequently for air shower development too. The most popular model
which has been used to simulate interactions of nucleons and nuclei is based on Regge
phenomenology with the super-critical Pomeron exchange. However, as mentioned above,
this model faced with a serious difficulties in description of single diffractive dissociation
in $p\bar{p}$ collisions. Moreover, the super-critical Pomeron model breaks the fundamental
principles of relativistic quantum theory such as unitarity, and this fact is often overlooked.
But only this pathology of the super-critical Pomeron model is enough to reject the
model from consideration. Recent accurate and complete analysis of experimental data
on hadron total cross sections rejects this model from statistical point of view. Another,
and sometime neglected, source of uncertainties is uncertainty provided by the measure-
ments of $pp$ total cross sections performed at Tevatron. Really, the CDF Collaboration
\cite{25} obtained $\sigma^{tot}_{pp} = 81.83 \pm 2.29$ mb which is considerably greater than those reported
by E710 (72.81 \pm 3.1 mb) \cite{26} and E811 (71.71 \pm 2.02 mb) \cite{27}. Such difference in the
measurements permits of a wide range of different extrapolations. Of course, the arising
uncertainty directly transfers to predictions for air showers. Namely, the main source of
uncertainty of air shower predictions comes from differences in modelling hadronic inter-
actions which cannot be eliminated by existing accelerator data. That is why an accurate
measurement of the $pp$ total cross section at LHC is of great importance since it would
allow to discriminate the different extrapolations and to make a selection among currently
used models. The study of $pA$ (proton-nucleus) collisions for the light nuclei at LHC is
also of greatest interest, of course, not only for fundamental particle physics but for air
shower physics as well.

At the same time it’s quite clear, that Quantum Field Theory provides a sound theoretical
basis with a definite guidelines how the fundamental interactions evolve with energy.
In this respect the discussed here global description of the hadron total cross sections
performed in the framework of general structures of local quantum field theory keeps a
preferable place. Thus an incorporation of the global pattern of hadronic interactions in
generally used generators of events would be extremely desired.
The next widely discussed subject is the question of origin of cosmic rays. Although cosmic ray particles were discovered almost one hundred years ago since the first announcement of their observation in 1912 [28], the problem of origin of cosmic rays especially of UHECRs particles has no solution so far. The total cosmic rays spectrum is shown in Fig. 16. The commonly accepted point of view is that at energies below 1 GeV the cosmic rays spectrum is dominated by particles coming from the Sun because the intensities at such energies are correlated with the Solar activity. At higher energies between 1 GeV and up to the knee region (see Fig. 16) there are several arguments including energetics that an origin of the cosmic rays is outside the Solar system but confines yet to the Galaxy. At still higher energies between the knee and the ankle, and finally, beyond \(10^{19}\) eV the situation becomes unclear, although the UHECRs are generally expected to have an extragalactic origin due to apparent isotropy, and the ankle is sometimes interpreted as a cross over from Galactic to extragalactic component. At any rate, it is generally believed that the bulk of the cosmic rays observed at the Earth is of extra-Solar origin.

Here we would like to suggest quite another new idea that the bulk of the cosmic rays observed at the Earth is of solely Solar origin. In particular, the UHECRs particles coming to the atmosphere of the Earth might be produced by reaction

\[
X_\odot + \odot \rightarrow P_\odot + \odot ,
\]

where we have used the notations: \(X_\odot\) for Galactic or extra-Galactic UHECRs particle, \(\odot\) for the Sun, \(P_\odot\) for UHECRs particle coming to the atmosphere of the Earth from the Sun. Due to reaction (21) almost all energy of \(X_\odot\) particle is transferred to \(P_\odot\) particle. The idea is based on the fact that the cross section of reaction (21) is in 4 orders greater than the cross section of direct interaction of \(X_\odot\) particle with the Earth. Of course, we did not concern of what is the source of the UHECRs in the Universe, one only claims that UHECRs particles coming to the atmosphere of the Earth are produced on the Sun.

In this respect we would like to remind an old idea suggested in [30] to consider the Virgo cluster as a source of the UHECRs. According to this idea the UHECRs particles, generated in M87 galaxy in Virgo cluster, diffuse from the center of Virgo in a postulated extragalactic field with the energy dependent diffusion coefficient, and they are focusing to the Sun by galactic magnetic field. It is remarkable that there is no GZK cutoff, and there is no large anisotropy in the model. Recently a new revival of this very interesting idea has been proposed. Introducing a simple Galactic wind in analogy to Solar wind it has been shown [31] that back-tracing the orbits of the highest energy cosmic rays events suggests that they may all come from the Virgo cluster, probably from the active radio galaxy M87. Figure 17 shows the directions of the cosmic rays events at that point when they leave the halo of our Galaxy in polar projection. In Fig. 17 the direction to the active Galaxy M87 (Virgo A), which is the dominant radio Galaxy in the Virgo cluster, is pointed out as well for reference. The two highest energy events are shown in Fig. 17 twice: in assuming (i) that they are protons, and (ii) that they are Helium nuclei (filled black symbols). The shaded band in Fig. 17 corresponds to the supergalactic plane. A remarkable observation made in the model calculations is that the directions of all tracks point North [31]. With exception of two events with highest energy, all other 11 events can be traced to within less 20° from Virgo A. Considering the uncertainty of the actual magnetic field distribution, it was found that all events are consistent with arising originally from Virgo A. Besides, if the two highest energy events are really Helium nuclei, then all 13 events point within 20 degrees of Virgo A. Of course, it is very interesting that
the simple model for a Galactic wind rather similar to the Solar wind may allow particle orbits at $10^{20}$ eV to be bent sufficiently to allow “trans-GZK” particles to arrive to the Sun from Virgo from different directions in agreement with the apparent isotropy in arrival directions. If the model assumptions might be confirmed then all powerful radio-galaxies might be considered as sources of the UHECRs. In that case the fantastic idea arises to use the powerful radio-galaxies as gigantic accelerators to set up particle interaction experiments in the sky [31]. The Sun may be used as a target, the atmosphere of the Earth – as a calorimeter to detect the highest energy events.

4 Conclusion

We did not intend in this article to present a full understanding the cosmic rays observations. Really we have only concerned very special but at the same time quite intriguing observation related to absence (GZK puzzle) of the predicted catastrophic cutoff (GZK effect) of the UHECRs spectrum at energy value about $10^{20}$ eV. Without any doubt, an observation of a significant flux of UHECRs particles with energy above the expected GZK cutoff value is of great interest, and many attempts have been undertaken to explain the existence of such particles. As mentioned above an explanation of these particles requires the existence of extremely powerful sources within so called GZK sphere with the radius about a few tens Mpc. There is evidence that such powerful radio-galaxies may really exist although this fact should be clearly confirmed by future experiments with the higher statistics.

It should be fair to note that there is a controversial point of view which means that there are no particles with energy above the GZK cutoff value, but the present results of AGASA and others, where such particles have been observed, are artefact of a combination of incorrect energy calibration, larger than predicted fluctuations in shower development, non gaussian tail in measurements etc. We did not touch this point of view at all. But here it should be pointed out the recent article of the HiRes Collaboration [32] where the HiRes measurement of the flux of ultrahigh energy cosmic rays with fluorescence technique shows a suppression at an energy of $6 \times 10^{19}$eV, exactly the expected cutoff energy. The statistical significance of the break in the spectrum identified with the GZK cutoff is $\sim 5\sigma$. The measured energy of the cutoff is $(5.6 \pm 0.7 \pm 0.9) \times 10^{19}$eV, where the first uncertainty is statistical and the second is systematic. At the same time Teshima (for AGASA Collaboration) [33] presented at the International Conference on High Energy Physics ICHEP2006 (Moscow, Russia, July 26–August 2, 2006) a new (preliminary) AGASA reanalysis with recent CORSIKA M.C. in which the number of events above $10^{20}$eV was reduced from 11 to 5–6, and the flux difference between AGASA and HiRes became less significant. Nevertheless the main conclusion in summary of the talk given by Teshima has been unchanged: “Super GZK particles exist”. This means that the GZK puzzle exists as well. In fact, the new (preliminary) AGASA data extend beyond the GZK cutoff energy with no apparent suppression and probably without dip and bump. However, it should be noted that the combined AGASA&HiRes data presented in Fig. 18 (Fig. 3 from Ref. [32]) clearly show the dip structure at the GZK cutoff energy as mentioned in the Introduction.

We also did not concern any exotic models to explain the existence of “trans-GZK” particles. Among them there are the so called “Z-burst” scenario, Top-Down models,
and even super-exotic explanation due to violation of Lorenz invariance; see e.g. excellent review article [34] and references therein. Our conjecture is the attempt to find the solution of the GZK puzzle in the fundamental dynamics of scattering from nuclei. Certainly, it needs to do much work else to convert the conjecture into strong statement. At the same time it is expected that next generation experiments in Astrophysics, especially in Cosmic Rays Physics, will be able to yield significant new information about fundamental processes in Particle Physics. Here the measurement of the UHECRs spectrum beyond the GZK cutoff is of great importance because such measurements being a grand element of Cosmic Rays Physics has a very deep relation with Particle Physics.

It seems the upcoming researches of particle interactions (in the sky and on the Earth) promise to represent the near future as an exciting epoch in science when the three branches of science Cosmology, Astrophysics and Particle Physics are very probably to be combined into unique common fundamental science such as CosmoAstroPartPhysology or CASP-Physics. Certainly, we believe in it.

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Figure 1: The total photo-pion production cross section for protons as a function of the photon energy in the proton rest frame (from Ref. [8]).
Figure 2: Energy loss length of protons in interactions with the CMBR photons (thick solid line). The dashed line shows the proton interaction length. The contribution of the pair production is shown with a thin line. The dotted line shows the neutron decay length (from Ref. [8]).
Figure 3: The experimental data on the UHECRs spectra from Fly’s Eye (blue triangles), AGASA (red circles), HiRes I (green triangles), and HiRes II (open squares) measurements (from Ref. [9]).
Figure 4: The total single diffraction cross-sections for $p(\bar{p})+p \rightarrow p(\bar{p})+X$ vs $\sqrt{s}$ compared with the predictions of the renormalized Pomeron flux model of Goulianos [16] (solid line) and of the model Gostman, Levin and Maor [17] (dashed line, labelled GLM).
Figure 5: The experimental data on the antiproton-deuteron total cross-section vs \( \sqrt{s} \) [7]. The curve is outcome of matching the theory and experiment [21].

Figure 6: The experimental data on the proton-deuteron total cross-section versus \( \sqrt{s} \) [7]. The curve is outcome of matching the theory and experiment [21].
Figure 7: The experimental data on the proton-antiproton total cross-section vs $\sqrt{s}$ [7]. Solid line represents our global fit [18] to the data. Statistical and systematic errors added in quadrature.

Figure 8: The experimental data on the proton-proton total cross-section versus $\sqrt{s}$ [7]. Solid line represents our global fit [18] to the data. Statistical and systematic errors added in quadrature.
Figure 9: The proton-proton total cross-section versus $\sqrt{s}$ with the cosmic-ray data points from Akeno Observatory and Fly’s Eye Collaboration. Solid line corresponds to our theory predictions [23].

Figure 10: The proton-proton total cross-section versus $\sqrt{s}$ at low energies. Solid line corresponds to our theory predictions [24].
Figure 11: The theoretically calculated elastic and inelastic defects of total cross section in scattering of (anti)protons from deuterons.

Figure 12: The theoretically calculated inelastic defect in the region of a maximum.
Figure 13: The scaled (anti)proton–deuteron total cross section in the region of a maximum of the inelastic defect.

Figure 14: The muon to electron ratio from experimental data of Kascade compared with simulations for p, He, O and Fe primaries at energies of about 1 PeV.
Figure 15: Average depth of shower maximum \( < X_{\text{max}} > \) vs. energy compared to the calculated values for protons (upper curves) and iron primaries (lower curves) in two models (from Ref. [9]; see references therein).
Figure 16: Compilation of measurements of the fluxes of cosmic rays. The data represent published results of the LEAP, Proton, Akeno, AGASA, Fly’s Eye, Haverah Park, and Yakutsk experiments. The dotted line shows $E^{-3}$ power-law for comparison. Approximate integral fluxes (per steradian) are also shown [29].
Figure 17: Directions in polar projection of the 13 highest energy cosmic ray events when they leave the halo of our Galaxy [31].
Figure 18: The combined AGASA&HiRes cosmic ray spectrum presented in Ref. [32], see Fig. 3 there.