Is astronomy possible with neutral ultra-high energy cosmic ray particles existing in the Standard Model?

P.G. Tinyakov[a,c] and I.I. Tkachev[b,c]
[a] *Université Libre de Bruxelles,*
CP225, Bvd du Triomphe, 1050 Bruxelles, Belgium
[b] *CERN Theory Division, CH-1211 Geneva 23, Switzerland*
[c] *Institute for Nuclear Research, Moscow 117312, Russia*
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The recently observed correlation between HiRes stereo cosmic ray events with energies $E \sim 10^{19}$ eV and BL Lacs occurs at an angle which strongly suggests that the primary particles are neutral. We analyze whether this correlation, if not a statistical fluctuation, can be explained within the Standard Model, i.e., assuming only known particles and interactions. We have not found a plausible process which can account for these correlations. The mechanism which comes closest — the conversion of protons into neutrons in the IR background of our Galaxy — still under-produces the required flux of neutral particles by about 2 orders of magnitude. The situation is different at $E \sim 10^{20}$ eV where the flux of cosmic rays at Earth may contain up to a few percent of neutrons pointing back to the extragalactic sources.

I. INTRODUCTION

In the last years it has been observed that various ultra-high energy cosmic ray (UHECR) data sets exhibit correlations with the BL Lacertae objects (BL Lac) at different level of significance [1, 2]. Recently, the HiRes stereo data have appeared which have unprecedented angular resolution of $\sim 0.6°$. This dataset shows correlations with BL Lacs at the angular scale compatible with the angular resolution. The statistical significance of the correlation is estimated to be of the order of 10^{-4} (11 coincidences observed at ~ 3 expected in the absence of correlations) [3, 4]. The absence of adjustable cuts makes it straightforward, for the first time, to predict the signal which should be observed in the future datasets if BL Lacs are sources of the ultra-high energy cosmic rays [5].

A most striking feature of the correlation found in the HiRes data is that it occurs at an angle which is much smaller than the typical deflection of a proton of corresponding energy in the Galactic magnetic field (GMF). The purpose of this paper is to investigate whether the existence of such correlations can be explained within the Standard Model, i.e., assuming only known particles and interactions. We will argue that this is extremely unlikely, if not impossible.

In order to proceed with the argument we need to make several assumptions. Although these assumptions are plausible, they may not be valid. If this be the case, the results of our analysis should be reconsidered.

The assumptions are as follows:

i) The fraction of correlating events at energy $E > 10^{19}$ eV is larger than $\sim 1\%$.

ii) The Galactic magnetic field around Earth location has a coherent component with the strength of order $2-3\ \mu G$.

iii) The distances to BL Lacs which are counterparts (sources) of correlating events are larger than $\sim$ 100 Mpc.

The validity of the assumption i) has been discussed in detail in Refs. [5]. Note that it is implicitly assumed here that energies of cosmic rays are measured correctly.

The assumption ii) is the widely accepted value of the Galactic magnetic field in the vicinity of the Earth (for recent reviews see, e.g., Refs. [6]). The precise magnitude of MGF is not important for the argument; its variations by a factor 2-3 would not change our conclusions.

Finally, the assumption iii) is needed because some of the BL Lacs which contribute to correlations have unknown redshifts. It is usually expected that these redshifts exceed $0.1-0.2$.

Given the assumptions i)–iii), the argument proceeds as follows. The deflection of a $E = 10^{20}$ eV proton in the 2 μG coherent field extending over 1 kpc is 1°. Most of the events, however, have much lower energies (for the events of energies $E > 10^{19}$ eV with the spectrum falling like $\sim 1/E^3$ the median energy is 1.5×10^{19} eV). Since the correlating events follow the same distribution [4], their typical deflections would be $\gtrsim 7°$. The correlation with the sources would therefore be destroyed. At such a small angular scale as observed, the correlations can survive in the following cases only:

1) There exist "windows" in the Galactic magnetic field with a very low value of the coherent component.

2) A fraction of primary particles is neutral.

3) A fraction of primaries is converted to neutral particles before entering the Galactic magnetic field, i.e., at least 1 kpc from the Earth (assuming the Galactic magnetic field does not extend further than $\sim$ 1 kpc from the disk).

We consider these three possibilities in Sects.II-V. In this paper we limit ourselves to mechanisms which are based on particles and interactions existing in the Standard Model. We show that none of such mechanisms can explain the observed correlation, unless very unlikely assumptions are made. In the last Sect.VI we summarize the arguments and present the conclusions.

II. MAGNETIC FIELDS

A. Galactic magnetic field

The Galactic magnetic field (GMF) consists of two components, the coherent and the turbulent one. The existence of the coherent component is the main reason why the UHECR-BL Lacs correlations at $E \sim 10^{19}$ eV cannot be explained by protons. In models which are currently in use, the coherent GMF extends to the whole Galaxy, being described by a simple analytic function. However, such a picture is probably an oversimplification. Observationally, there are many anomalies and features in the Galactic magnetic field. It is not totally excluded that the coherent component is "patchy". In other words, there may exist "windows" where the coherent component is negligible. In this case the ultra-high energy protons may cross the GMF undeflected when they come from the directions of these "windows". One may thus try to explain the observed correlations by the existence of such windows.

For this mechanism to work the random component of the GMF in windows also has to satisfy some requirements. The deflections of protons in the random field is estimated as follows

$$\delta_r = 0.5^\circ \cdot \left(\frac{10^{19}\ \mathrm{eV}}{E}\right)\left(\frac{B_r}{4\ \mu\mathrm{G}}\right)\sqrt{\frac{D}{1\ \mathrm{kpc}}}\sqrt{\frac{L_c}{1\ \mathrm{pc}}}\ , \qquad (1)$$

where E is the energy of proton, B_r and L_c are the rms value and the coherence length of the random magnetic field, respectively, while D is the propagation distance. This deflection has to be (much) smaller than 0.5°.

The coherence length L_c is the most uncertain of the above parameters. Quite often a large values of L_c up to $L_c \sim 50$ pc are assumed. On the contrary, in those regions of the sky where the spectrum of the magnetic field fluctuations was measured, L_c turns out to be small [7]. For instance, in Ref. [8] the linearly polarized continuum emission was studied in the test region near the Galactic plane covering the range $325.5^\circ < l < 332.5^\circ$, $-0.5^\circ < b < 3.5^\circ$. Polarized emission was found to originate mainly at the distance of ~ 3.5 kpc. Interestingly, two large areas of a few square degrees each were found to be devoid of polarization. It was argued that these voids were produced by the foreground in which the magnetic field is disordered, with the coherence length being $L_c \sim 0.1 - 0.2$ pc. In these voids, the projection of the coherent component of the magnetic field on the line of sight was found to be < 0.15 of the rms value of the random field strength. In the rest of the test region, i.e. outside of the voids, the coherence length is much larger, but still the outer scale of turbulence did not exceed 2 pc [9]. Thus, the existence of regions with $\delta_r < 0.5^\circ$ does not seem impossible.

This mechanism has a specific signature which is straightforward to test. If there exist "windows" with the small coherent component of GMF, the Faraday rotation measures must be small in these windows as well. In other words, the Faraday rotations in the directions of correlating UHECR events must be anomalously small. This may be tested statistically by comparing the distribution of Faraday rotations in the direction of *correlating* events with the distribution of Faraday rotations in the random directions selected according to the distribution of BL Lacs and *all* cosmic ray events[37]. We have performed this test with the existing data and found that the two distributions are indeed different (Faraday rotations in the directions selected with real data are anomalously small) with the significance of $\sim 4\%$ according to the Kolmogorov-Smirnov test. This is not a very significant deviation. The result demonstrates, however, that the method may work quite well with the future larger datasets.

Although the existence of "windows" in the coherent component of the Galactic magnetic field goes against the standard lore, a much better understanding of the Galactic magnetic field is required to definitely rule it out.

B. Extragalactic magnetic fields

For the mechanism outlined above to work, the extragalactic magnetic fields have to satisfy certain requirements (which also apply to the scenarios considered in Sec. IV). The extragalactic magnetic fields are not measured. Computer simulations indicate [10, 11] that the magnetic field strength in voids between clusters can be very small, $B_r < 10^{-12}$ G, while the coherence length can easily be significantly smaller than 1 Mpc. Eq. (1) then shows that the deflections in voids are negligible. It is interesting to note that EGMF with such small magnitude are in principle measurable in observations of TeV gamma-rays from distant blazars [12].

The strength of the field in filaments is larger. However, the probability to cross many filaments is small and regions with small deflections can occupy rather large fraction of the sky area [10, 11] (see however [13]). Overall, the model where the extragalactic magnetic fields are sufficiently small and do not spoil correlations is acceptable at present.

III. NEUTRAL PRIMARIES

Among known neutral particles the following are sufficiently stable to propagate over extragalactic distances: neutrino, photon and atoms. In this section we discuss the possibility to explain correlations by assuming that primary cosmic rays are composed of these particles.

Both neutrino and photon initiate air showers deeper in the atmosphere than the hadronic primary particles. Therefore, these models can be falsified with already existing data by, e.g., comparing the $X_{\max}$ distributions of the correlating events with that of the whole set. Since the corresponding data are still unpublished, we briefly discuss the models based on neutrino and photon and show that they have difficulties *per se*, even without referring to $X_{\max}$ distributions.

a. **Neutrino.** At $E \gtrsim 10^{19}$ eV the neutrino cross-section with protons is smaller by a factor of $\sim 3 \times 10^{-7}$ than the *pp* cross-section [14]. Therefore, the optical depth of the atmosphere for neutrinos is 3×10^{-5}. On the other hand, at this energy the neutrino flux cannot exceed the flux of hadronic cosmic rays by more than a factor of 50 [15]. It follows that at most (a few) $\times 10^{-4}$ of all cosmic ray events can be due to neutrinos. This is more than a factor of 10 lower than needed to explain correlations. Thus, neutrino with the standard weak interactions cannot explain correlations observed in the HiRes data set.

A "genuine" (hypothetical) neutrino mechanism would involve strong neutrino interactions with the atmosphere at high energies [16]. As such a behavior in not a part of the Standard Model, the corresponding speculations fall outside of the scope of the present paper.

Another possibility which exists within the minimal extention of the Standard Model by the non-zero neutrino masses, the Z-burst mechanism [17], requires an unnaturally large flux of neutrinos at $E > 10^{22}$ eV which is in conflict with the limits on neutrino flux from radio experiments [18]. The particles observed at Earth in this mechanism are mostly photons produced in the interactions of UHE neutrinos with the cosmological neutrino background on their way to the Earth. Low radio-background and small values of EGMF are required to avoid the conflict with the upper bound on the diffuse flux of gamma rays [19].

b. **Photon.** A set of conditions under which the UHE photons can reach the Earth from BL Lacs was considered in Ref. [20]. On their way the photons interact with the CMBR and radio background photons producing e^+e^- pairs, one of these particles typically carrying most of the energy. These leading particles in turn Compton up-scatter CMBR photons to the energy almost equal to the energy of the original photon. This process is usually referred to as the electromagnetic cascade. The developing electromagnetic cascade can reach the Earth from several hundred megaparsecs with energy $E \sim 10^{19}$ eV if the following conditions are satisfied:

- the radio-background is small, smaller than the theoretically expected value;
- the injection spectrum $\propto E^{-\alpha}$ is hard, $\alpha \lesssim 1.5$;
- maximum energy of photons at the source reaches 10^{23} eV
- EGMF are small, $B < 10^{-12}$ G;
- sources are predominantly photonic, $N_\gamma/N_p \gtrsim 10^2$.

These conditions impose extreme requirements on the astrophysical sites where such photons can be produced. There are no candidates known which could satisfy these requirements.

c. **Atoms.** It may, in principle, happen that in the cosmological radiation field the proton produces an e^+e^--pair and "dresses" itself with the electron forming an hydrogen atom and emitting a free positron. The differential cross section of electromagnetic pair production by a single photon in the Coulomb field of a nucleus with subsequent capture of the electron is estimated as [21]

$$\frac{d\sigma}{dE_p} = \frac{4\pi\alpha^6 Z^5}{m_e^2} \frac{1}{E_p},$$

where Z is the electric charge of an ion and the positron energy E_p is supposed to be much larger than m_e. Multiplying the cross section integrated over energy by the density of the CMB photons one may estimate the rate of the formation of hydrogen atoms, $Z = 1$, as

$$R_{\text{formation}} \sim 10^{-5}\ \text{Mpc}^{-1}.$$

The decay rate (ionization on the CMB radiation) is estimated in a standard way by using the Klein-Nishina cross section. One finds

$$R_{\text{decay}} \sim 100\ \text{Mpc}^{-1}.$$

Thus, the fraction of neutral particles (atoms) produced by this mechanism is of the order of 10^{-7}, which is too small to explain correlations.

As a side remark note that for a heavy nuclei the rates of radiative capture and ionization are comparable when $Z \approx 25$. This corresponds to the typical equilibrium charge of a heavy ion (iron or heavier) propagating in the CMBR.

IV. CONVERSION TO NEUTRONS IN OR NEAR THE GALAXY

In order to be able to fly over 1 kpc (the thickness of the Galactic magnetic field) a neutral particle created at the outskirts of the Galaxy has to be sufficiently stable. At energy 10^{19} eV this implies for the rest-frame lifetime

$$\tau_0 > 10\,\text{s}\ \left(\frac{m}{1\ \text{GeV}}\right) \left(\frac{10^{19}\ \text{eV}}{E}\right),$$

where E and m are the energy and the mass of the particle, respectively. Among known particles which we have not yet discussed only neutrons satisfy this requirement. In this section we consider various mechanisms of neutron creation in or near the Galaxy.

There are several ways to produce neutrons in the Standard Model: photodisintegration of nuclei, photoproduction on background photons by protons, creation in pp reactions and in inverse β-decay on background neutrinos or photons. We consider these mechanisms in turn and argue that none of them can produce a sufficient fraction of neutrons in the cosmic ray flux.

A. Inverse β-decay on background neutrinos.

The simplest of the above mechanisms is the inverse beta-decay, $p + \bar{\nu} \to n + e^+$. The cross section of this reaction is [22]

$$\sigma(p\bar{\nu} \to ne^+) \simeq \frac{1}{\pi} G_F^2 (g_V^2 + 3g_A^2) E^2,$$

where $g_V^2 + 3g_A^2 \sim 5.7$ and E is the energy of neutrino in the proton rest frame. When E reaches ~ 1 GeV the cross section levels out and stabilizes at the value of $\sigma_{\max} \sim 10^{-14}$ barn. With this maximum value taken for the estimate, the rate of the conversion is

$$R_{\max} \sim 4 \times 10^{-12}\ \mathrm{Mpc}^{-1}. \tag{2}$$

Thus, these processes are totally negligible.

B. Creation of neutrons in the radiation fields.

The process of creation of neutrons in interactions of CR primaries with the background photons produces the largest contribution, therefore we consider it in most detail.

1. *Galactic and extragalactic radiation fields and reaction rates.*

In the laboratory frame, the rate of reactions with the photon background is given by the standard expression,

$$R = \int d^3p\, n(\mathbf{p})(1 - v\cos\theta)\sigma(\tilde{\omega}), \tag{3}$$

where $n(\mathbf{p})$ is the photon density in the laboratory frame, $\sigma(\tilde{\omega})$ is the cross section of the relevant reaction in the rest frame of the primary particle as the function of the energy of the incident photon $\tilde{\omega} = \gamma p(1 - v\cos\theta)$, γ is the gamma-factor of the primary particle in the laboratory frame and v is its velocity ($\gamma = 1/\sqrt{1-v^2}$). In what follows we assume $\gamma \gg 1$.

In the case of the isotropic background this expression may be simplified. Integrating over angles we find

$$R(\gamma) = \frac{2\pi}{\gamma^2} \int_0^\infty dp\, n(\mathbf{p}) \int_0^{2\gamma p} d\omega\, \omega\sigma(\omega). \tag{4}$$

For the black body radiation with temperature T one has

$$n(\mathbf{p}) = n_{\mathrm{T}}(p) \equiv \frac{2}{(2\pi)^3} \frac{1}{\exp(p/T) - 1}. \tag{5}$$

This gives the answer in the case of CMBR. Other backgrounds, Galactic and extragalactic, are usually characterized in the literature by the spectral energy distribution $I(\nu, \mathbf{i})$ (energy per unit frequency per unit solid angle) which in turn is usually quoted in terms of the Planck function $B_\nu(T)$ and emissivity ϵ

$$I(\nu, \mathbf{i}) = \epsilon(\nu, \mathbf{i})\, B_\nu(T). \tag{6}$$

Here $\mathbf{i}$ stands for the unit vector in the direction of observation. For the black body radiation $\epsilon(\nu, \mathbf{i}) = 1$. The Planck function, being written as a function of photon momentum $p = 2\pi\nu$, takes the form

$$B_p(T) = p^3 n_{\mathrm{T}}(p). \tag{7}$$

Therefore, the photon number density for the background with the known emissivity is given by the expression

$$n(\mathbf{p}) = \epsilon(\mathbf{p}/2\pi)\, n_{\mathrm{T}}(p). \tag{8}$$

In what follows we will be interested in the Galactic and extragalactic far-infrared backgrounds (FIRB) (for a recent review see [23]). According to Ref [24], the isotropic extragalactic FIRB can be parameterized by

$$\epsilon(p) = 1.3 \times 10^{-5}\, (p/p_0)^{0.64}, \tag{9}$$

where $p_0 = 144$ K (which corresponds to $\nu_0 = 100\ \mathrm{cm}^{-1}$), while the temperature parameter in $n_{\mathrm{T}}(p)$ corresponds to $T = 18.5$ K.

The Galactic FIRB has been measured by COBE/DIRBE. The spectral energy density $I(\nu, \mathbf{i})$ as a function of galactic coordinates can be downloaded from [25]. The radiation is dominated by the Galactic plane where the Galactic bulge is by far the brightest region. One may approximate this radiation field by a point source in the Galactic center. We have verified that this approximation gives a good agreement with the exact calculations for cosmic ray trajectories which do not pass close to the Galactic center.

According to [26], the averaged spectral properties of the Galactic FIRB can be described by $n_{\mathrm{T}}(p)$ with $T = 20.4$ K and $\epsilon(p) \propto p^2$. Therefore, in what follows for the Galactic FIRB we use

$$\epsilon(\mathbf{p}) = \frac{I_0}{r^2}\, p^2\, \delta(\mathbf{n} - \mathbf{n}_0), \tag{10}$$

where I_0 is the normalization factor, $\mathbf{n}_0$ is the unit vector in the direction from the Galactic center, and r is the distance to the Galactic center. The constant I_0 can be found by normalizing the total luminosity within the Sun orbit to the measured value $L_G = 1.8 \times 10^{10}\ L_\odot \sim 7 \times 10^{36}$ W [26]. We find

$$I_0 = \frac{63 L_G}{8\pi^4 T^6}.$$

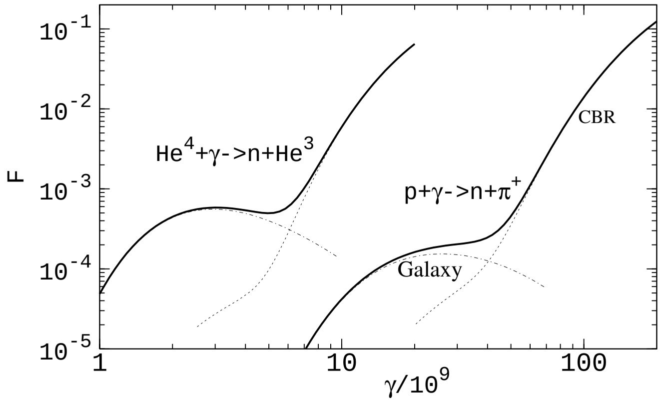

FIG. 1: The fraction F of neutrons produced per one incident particle (solid lines) in the reactions ${}^4\mathrm{He}+\gamma \to {}^3\mathrm{He}+n$ (left curve) and $p+\gamma \to n+\pi^+$ (right curve) on the background radiation fields as a function of the γ-factor of the incident particle. Dotted and dashed-dotted lines show contributions of the extragalactic and Galactic backgrounds, respectively.

The reaction rate Eq. (3) in this case can be expressed as

$$R(\gamma, r, \theta) = \frac{126}{64\pi^7}\frac{L_G}{T^6 r^2}(1-\mu)\int_0^\infty \frac{dp\, p^4\, \sigma(\tilde{\omega})}{\exp(p/T)-1}. \quad (11)$$

Here $\tilde{\omega} \equiv \gamma p(1-\mu)$, $\mu \equiv \cos\theta$ and θ is the collision angle between the CR primary and the background photon.

2. *Conversion in the extragalactic space.*

The fraction of neutrons created over the distance dl is Rdl. Due to the finite neutron lifetime the fraction of neutrons which reach the solar system is given by

$$F(\gamma) = R\int_0^\infty \mathrm{e}^{-l/\lambda} dl = R\lambda, \quad (12)$$

where R is given by the expression Eq. (4) and λ is the mean propagation distance of the free neutron,

$$\lambda = 0.86\,\frac{\gamma}{10^{11}}\,\mathrm{Mpc}.$$

The function $F(\gamma)$ is shown in Fig. 1 by dotted lines for the two reactions, the pion photoproduction $p+\gamma \to n+\pi^+$ (right curve) and the reaction of nuclear photodissociation ${}^4\mathrm{He}+\gamma \to {}^3\mathrm{He}+n$ (left curve). In these calculations the experimentally measured cross sections of the corresponding reactions were used [27, 28].

3. *Conversion in the Galactic infrared radiation field.*

In this case the number of neutrons produced per one incident particle is determined by the rate (11) integrated along the particle trajectory,

$$F(\gamma, \psi) = \int_0^\infty dl\, R(\gamma, r, \theta)\, \mathrm{e}^{-l/\lambda}, \quad (13)$$

where l is the distance from the Sun along the trajectory and r is the distance from the current point to the Galactic center. In the case when the radiation field is approximated by the single source in the Galactic center, the particle trajectory is completely characterized by the angle ψ which it forms with the direction to the Galactic anti-center ($\psi = \pi$ corresponds to the trajectory which passed through the Galactic center). In terms of this angle the distance r entering Eq. (13) reads

$$r = \sqrt{D^2 + l^2 + 2Dl\cos\psi},$$

while the collision angle θ is

$$\cos\theta = -\frac{D\cos\psi + l}{r},$$

where $D \approx 8$ kpc is the distance from the Sun to the Galactic center

The Galactic contribution $F(\gamma, \psi)$ to the fraction of the produced neutrons in the case $\psi = 90^\circ$ is shown in Fig. 1 by the dashed-dotted lines for the reactions $p+\gamma \to n+\pi^+$ (right curve) and ${}^4\mathrm{He}+\gamma \to {}^3\mathrm{He}+n$ (left curve). Here again we have used the cross sections measured experimentally.

As far as the correlations observed in the HiRes data at $E > 10^{19}$ eV are concerned, the relevant range of the γ-factors is $(1-2)\times 10^{10}$. In this region the reaction ${}^4\mathrm{He}+\gamma \to {}^3\mathrm{He}+n$ is irrelevant for distant sources. Indeed, in the case of ${}^4\mathrm{He}$ these γ-factors correspond to energies $(4-8)\times 10^{19}$ eV. The helium nuclei of such energies do not propagate over several hundred megaparsecs [29], so they cannot be present in the cosmic ray flux coming from BL Lacs. The other reaction, $p+\gamma \to n+\pi^+$, produces a fraction of neutrons at the level of (a few) $\times\, 10^{-4}$ (see Fig. 1), which is not sufficient to explain correlations by almost two orders of magnitude.

C. Neutron production in collisions with interstellar matter.

Neutrons can be produced in collisions of hadronic primaries with the interstellar gas in the galaxy. The conversion probability is given by the optical depth $\tau = \mathcal{N}\sigma_g$, where $\mathcal{N}$ is the column density of the intervening interstellar gas in a given direction and σ_g is the interaction cross section. In order to explain correlations [3, 4] one needs $\tau \gtrsim 10^{-2}$.

A typical value of the HI (neutral hydrogen) column density in directions of the Galactic poles is $\mathcal{N}_{\mathrm{HI}} \approx 10^{20}\ \mathrm{cm}^{-2}$ [30]. Using as an upper limit for σ_g the value of the total pp cross-section at relevant energies, $\sigma_{pp} \approx$ 100 mb $= 10^{-25}\ \mathrm{cm}^2$, one finds $\tau_{pp} \sim 10^{-5}$, which is too small to produce the required fraction of neutrons.

The argument can be rephrased in a different way. One may assume that a mass fraction η of the Galactic halo consists of baryons including nuclei, neutral and ionized gas and possibly dark baryons. The column mass density of matter in the direction of the Galactic anticenter, as deduced from the Milky Way rotational curve, is $\sim 10^{22}$ GeV cm^{-2} [31], and therefore the column density of baryons is $\sim \eta\, 10^{22}$ cm^{-2}. To reproduce the required rate of pn conversions one would need a fraction $\eta \gtrsim 10$, which is clearly impossible.

As a side remark let us point out that neutrons can be, in principle, produced in the interactions of primary protons with a non-baryonic dark matter in the Galactic halo. Parameterizing the relevant cross-section in the energy range of interest as $\sigma \equiv E_0^{-2}$ and making use of the matter column density of the Galactic halo cited above we find

$$\tau_{p\mathrm{DM}} \sim 10^{-2} \left(\frac{1\ \mathrm{TeV}}{E_0}\right)^2 \left(\frac{1\ \mathrm{eV}}{m_{\mathrm{DM}}}\right),$$

where m_{DM} is the mass of the dark matter particle. Among the scenarios involving new physics, this one has several advantages. It automatically provides a normal shower development in the atmosphere (contrary to the models with new particles as neutral messengers [32, 33]) and avoids the problem of messenger production in AGNs [34]. In addition, we know from precision cosmological data that the non-baryonic dark matter must exist. Correlations in this scenario should dissappear at $E \lesssim 10^{17}$ eV due to the final life-time of the neutron. Note also that one should expect the existence of the Greisen-Zatsepin-Kuzmin cut-off [35, 36] in the cosmic ray spectrum in this model.

V. CONCLUSIONS

In this paper we have considered different mechanisms which could potentially explain the observed correlations of the cosmic ray events with BL Lacs at the energy $E \sim 10^{19}$ eV and the angle $\sim 0.6°$ coincident with the angular resolution of the HiRes experiment. We found that the mechanisms which assume only known particles and interactions under-produce the flux of neutral particles needed to explain these correlations by at least two orders of magnitude.

There remains a possibility of the astrophysical solution, which is related to our insufficient knowledge of the Galactic magnetic field. The observed tight correlations can potentially be explained if there exist "windows" in the Galactic magnetic field with a very low value of the coherent component of the field and a small coherence length of the turbulent component. Though this possibility is exotic, it cannot be ruled out at present.

The mechanisms which we have discussed in this paper are based on the known physics, i.e. they certainly operate in Nature provided the cosmic ray flux contains light nuclei or protons. One of these mechanisms, the conversion of protons to neutrons, implies that at energies around 10^{20} eV a few percent of the ultra-high energy protons (cf. Fig. 1) get converted into neutrons and cross the Galactic magnetic field undeflected. Therefore, if the cosmic rays with the energy around the GZK cutoff are protons, there must be a few percent fraction of them that point back to the sources with the accuracy better than a fraction of a degree, provided the extragalactic magnetic fields are small. With a large statistics, this may allow to measure separately the Galactic and extragalactic magnetic fields and to verify by an independent method the chemical composition of UHECR.

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