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IS ASTRONOMY POSSIBLE WITH NEUTRAL ULTRAHIGH ENERGY COSMIC RAY PARTICLES EXISTING IN THE STANDARD MODEL?

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The recently observed correlation between HiRes stereo cosmic ray events with energies $E \sim 10^{19}$ eV and BL Lacertae objects occurs at an angle that 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 that can account for these correlations. The mechanism that 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 two 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, indicating their extragalactic sources.

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1. INTRODUCTION

It has been observed recently that various ultrahigh-energy cosmic-ray (UHECR) data sets exhibit correlations with the BL Lacertae objects (BL Lac) at different levels of significance [1, 2]. The HiRes stereo data with the unprecedented angular resolution near 0.6° appeared recently. 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} (eleven coincidences observed at about 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 that should be observed in the future data sets if BL Lacs are sources of the ultrahigh-energy cosmic rays [5].

The most striking feature of the correlation found in the HiRes data is that it occurs at an angle much smaller than the typical deflection of a proton of the 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 argue that this is extremely unlikely, if not impossible.

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.

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

2) The GMF around the Earth location has a coherent component with the strength of the order of 2–3 μG.

3) The distances to BL Lacs that are counterparts (sources) of correlating events are larger than 100 Mpc.

The validity of assumption 1 was discussed in detail in Ref. [5]. We note that it is implicitly assumed there that energies of cosmic rays are measured correctly.

Assumption 2 involves the widely accepted value of

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the GMF in the vicinity of Earth (see, e. g., Refs. [6] for recent reviews). The precise magnitude of the GMF is not important for the argument; its variations by a factor of 2 to 3 would not change our conclusions.

Finally, assumption 3 is needed because some of the BL Lacs that contribute to correlations have unknown red shifts. It is usually expected that these red shifts exceed 0.1–0.2.

Given assumptions 1–3, 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 decreasing as $1/E^3$, the median energy is $1.5 \cdot 10^{19}$ eV). Since the correlating events follow the same distribution [4], their typical deflections are more than 7°. The correlation with the sources is therefore destroyed. At such a small angular scale as observed, the correlations can survive in the following cases only.

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

2) A fraction of primary particles (primaries) is neutral.

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

We consider these three possibilities in Secs. 2–5. We limit ourselves to mechanisms 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 Sec. 6, we summarize the arguments and present the conclusions.

2. MAGNETIC FIELDS

2.1. Galactic magnetic field

The 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 that are currently in use, the coherent GMF extends to the whole Galaxy, being described by a simple analytic function. But such a picture is probably an oversimplification. Observationally, there are many anomalies and features in the GMF. 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 ultrahigh-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 deflection of protons in the random field is estimated as

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

where E is the energy of proton, B_r and L_c are respectively the rms value and the coherence length of the random magnetic field, and 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, the linearly polarized continuum emission was studied in Ref. [8] in the test region near the Galactic plane covering the range of the Galactic coordinates $325.5^\circ < l < 332.5^\circ$, $-0.5^\circ < b < 3.5^\circ$. Polarized emission was found to originate mainly at the distance about 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 $L_c \approx 0.1$–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 less than 0.15 of the rms value of the random field strength. In the rest of the test region, i. e., outside 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 that is straightforward to test. If there exist windows with a small coherent component of the GMF, the Faraday rotation measures must also be small in these windows. 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 random directions selected in accordance with the distribution of BL Lacs and all cosmic ray events[1]. 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 approximately 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 data sets.

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

2.2. Extragalactic magnetic fields

For the mechanism outlined above to work, the extragalactic magnetic fields (EGMFs) have to satisfy certain requirements (which also apply to the scenarios considered in Sec. 4). The EGMFs 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. Equation (1) then shows that deflections in the voids are negligible. It is interesting to note that EGMFs with such a 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. But the probability to cross many filaments is small and regions with small deflections can occupy rather large fraction of the sky area [10, 11] (however, see [13]). Overall, the model where the EGMFs are sufficiently small and do not spoil correlations is currently acceptable.

3. NEUTRAL PRIMARIES

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

Both neutrinos and photons initiate air showers deeper in the atmosphere than the hadronic primary particles. Therefore, these models can be falsified with the already existing data, e. g., by 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.

3.1. Neutrinos

At $E \gtrsim 10^{19}$ eV, the cross section of the neutrino interaction with protons is smaller by a factor of about $3 \cdot 10^{-7}$ than the *pp* cross section [14]. Therefore, the optical depth of the atmosphere for neutrinos is $3 \cdot 10^{-5}$. 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)$\cdot 10^{-4}$ 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]. Because such behavior is not part of the Standard Model, the corresponding speculations fall outside the scope of the present paper.

Another possibility existing within the minimal extention of the Standard Model by nonzero 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 on the earth in accordance with this mechanism are mostly photons produced in the interactions of the ultrahigh-energy neutrinos with the cosmological neutrino background on their way to Earth. Low radio background and small values of the EGMF are required to avoid a conflict with the upper bound on the diffuse flux of gamma rays [19].

3.2. Photons

A set of conditions under which the ultrahigh-energy photons can reach Earth from BL Lacs was considered in Ref. [20]. On their way, the photons interact with the cosmic microwave background radiation (CMBR) and radio-background photons and produce 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

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[1] One may construct this set by choosing the directions to BL Lacs correlating with the Monte-Carlo simulated cosmic ray events. In this way the distributions of both BL Lacs and the cosmic ray events are taken into account.

reach Earth from several hundred megaparsecs with the energy $E \sim 10^{19}$ eV if the following conditions are satisfied:

a) the radio background is small, smaller than the theoretically expected value;

b) the injection spectrum proportional to $E^{-\beta}$ is hard, $\beta \lesssim 1.5$;

c) the maximum energy of photons at the source reaches 10^{23} eV;

d) the EGMFs are small, $B < 10^{-12}$ G;

e) the sources are predominantly photonic, $L_\gamma / L_p \gtrsim 10^2$, where L_γ and L_p are the photon and proton luminosity of the source.

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

3.3. Atoms

In principle, it may happen that a proton produces an e^+e^- pair in the cosmological radiation field and "dresses" itself with an electron, forming a 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 the subsequent capture of an 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 the ion, α is the fine-structure constant, 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 CMBR photons, we estimate the rate of the formation of hydrogen atoms, $Z = 1$, as

$$R_{form} \sim 10^{-5}\ \mathrm{Mpc}^{-1}.$$

The decay rate (ionization on the CMBR) is estimated in the standard way by using the Klein–Nishina cross section. We find

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

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, we note that for 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.

4. CONVERSION TO NEUTRONS IN OR NEAR THE GALAXY

To be able to fly over 1 kpc (the thickness of the GMF), a neutral particle created at the outskirts of the Galaxy has to be sufficiently stable. At the energy 10^{19} eV, this implies

$$\tau_0 > 10\ \mathrm{s}\frac{m}{1\ \mathrm{GeV}}\frac{10^{19}\ \mathrm{eV}}{E}$$

for the rest-frame lifetime, where E and m are the energy and the mass of the particle. Among the known particles that 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, and creation in pp reactions and in the 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.

4.1. Inverse β-decay on background neutrinos

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

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

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

$$R_{max} \approx 4 \cdot 10^{-12}\ \mathrm{Mpc}^{-1}. \qquad (2)$$

Thus, these processes are totally negligible.

4.2. Creation of neutrons in radiation fields

The process of creation of neutrons in interactions of the cosmic-ray primaries with the background photons produces the largest contribution, and we therefore consider it in greatest detail.

4.2.1. 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 $\mathbf{p}$ is the photon momentum, $n(\mathbf{p})$ 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 a 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 speed in the units of the speed of light ($\gamma = 1/\sqrt{1-v^2}$). We assume $\gamma \gg 1$ in what follows.

In the case of an isotropic background, this expression can 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 black-body radiation with a temperature T, we have

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

This gives the answer in the case of the 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 is in turn usually expressed 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, $\mathbf{i}$ is the line-of-sight unit vector. For black-body radiation, $\epsilon(\nu, \mathbf{i}) = 1$. The Planck function, written as a function of the photon momentum $p = 2\pi\nu$, takes the form

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

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

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

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

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

where $p_0 = 144$ K (which corresponds to $\nu_0 = 100$ cm^{-1}), while the temperature parameter in $n_T(p)$ 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. This radiation field can be approximated 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 that do not pass close to the Galactic center.

According to [26], the averaged spectral properties of the Galactic FIRB can be described by $n_T(p)$ with $T = 20.4$ K and $\epsilon(p) \propto p^2$. In what follows, we therefore use

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

for the Galactic FIRB, where I_0 is the normalization factor, $\mathbf{n} = \mathbf{p}/p$, $\mathbf{n}_0$ 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 $L_G = 1.8 \cdot 10^{10} L_\odot \approx 7 \cdot 10^{36}$ W [26], where $L_\odot$ is the Sun luminosity. We thus find

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

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

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

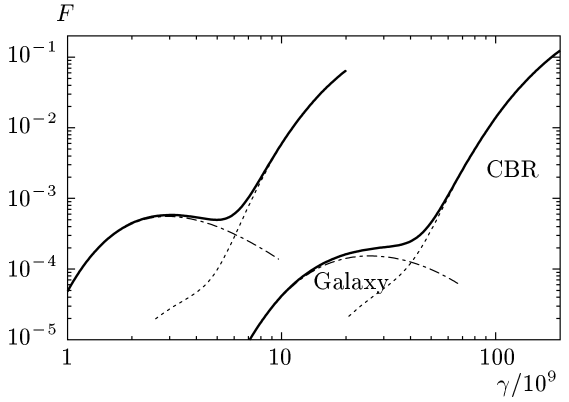
where $\tilde{\omega} = \gamma p(1 - \cos\theta)$ for an ultrarelativistic incident particle and θ is the collision angle between the cosmic-ray primary and the background photon.

4.2.2. Conversion in the extragalactic space

The fraction of neutrons created over the distance dl is $R dl$. Due to the finite neutron lifetime, the fraction of neutrons that reach the Solar system is given by

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

where R is given by Eq. (4) and



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 dash-dotted lines respectively show contributions of the extragalactic (CBR) and Galactic backgrounds

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

is the mean propagation distance of the free neutron.

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

4.2.3. Conversion in the Galactic infrared radiation field

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

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

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 where the radiation field is approximated by a single source in the Galactic center, the particle trajectory is completely characterized by the angle ψ that it forms with the direction to the Galactic anticenter ($\psi = \pi$ corresponds to the trajectory that passes through the Galactic center). In terms of this angle, the distance r entering Eq. (13) is given by

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

and 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 $\psi = 90°$ is shown in Figure by the dash-dotted lines for the reactions $p+\gamma \to n+\pi^+$ and ${}^4\mathrm{He}+\gamma \to {}^3\mathrm{He}+n$. Here, we have again 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) $\cdot 10^{10}$. In this range, 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) $\cdot 10^{19}$ eV. The helium nuclei of such energies do not propagate over several hundred megaparsecs [29], and therefore 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) $\cdot 10^{-4}$ (see Figure), which is not sufficient to explain correlations by almost two orders of magnitude.

4.3. 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. To explain correlations [3, 4], $\tau \gtrsim 10^{-2}$ is required.

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

The argument can be rephrased in a different way. We may assume that a mass fraction η of the Galactic halo consists of baryons including nuclei, neutral gas, 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 of the order of $10^{22}\ \mathrm{GeV\ cm}^{-2}$ [31], and therefore the column density of baryons is of the order of $\eta \cdot 10^{22}\ \mathrm{cm}^{-2}$. To reproduce the required rate of pn conversions, we would need a fraction $\eta \gtrsim 10$, which is clearly impossible.

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

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

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 the active Galactic nuclei [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 lifetime of the neutron. We also note that the existence of the Greisen – Zatsepin – Kuzmin cutoff [35, 36] in the cosmic ray spectrum should be expected in this model.

5. CONCLUSIONS

In this paper, we have considered different mechanisms that 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 near 0.6° coincident with the angular resolution of the HiRes experiment. We found that the mechanisms that 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 an astrophysical solution, which is related to our insufficient knowledge of the GMF. The observed tight correlations can potentially be explained if there exist windows in the GMF with a very low value of the coherent component of the field and a small coherence length of the turbulent component. Although this possibility is exotic, it cannot be excluded at present.

The mechanisms 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 ultrahigh-energy protons (cf. Figure) are converted into neutrons and cross the GMF undeflected. Therefore, if the cosmic rays with the energy around the Greisen – Zatsepin – Kuzmin 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, if the EGMFs are small. With a large statistics, this may allow measuring the GMF and EGMFs separately and verifying the chemical composition of UHECR by an independent method.

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