Neutron Oscillations to Parallel World: Earlier End to the Cosmic Ray Spectrum?

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Present experimental data do not exclude fast oscillation of the neutron n to its degenerate twin from a hypothetical parallel sector, the so called mirror neutron n'. We show that this effect brings to a remarkable modifications of the ultrahigh-energy cosmic ray spectrum testable by the present Pierre Auger Observatory (PAO) and Telescope Array (TA) detector, and the future JEM-EUSO experiment. In particular, the baryon non-conservation during UHECR propagation at large cosmological distances shifts the beginning of the GZK cutoff to lower energies, while in presence of mirror sources it may enhance the spectrum at $E \gtrsim 100$ EeV. As a consequence, a significant reduction of the expected diffuse cosmogenic neutrino flux is predicted.

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There may exist a hidden parallel sector that is an exact copy of our particle sector so that each ordinary particle: electron e, proton p, neutron n etc. has its mass degenerate twin: e', p', n' etc. [1]. These so called mirror particles are sterile to our strong and electroweak interactions $SU(3) \times SU(2) \times U(1)$ but have their own gauge interactions $SU(3)' \times SU(2)' \times U(1)'$ with exactly the same couplings. Mirror baryons are viable as *asymmetric* dark matter provided the parallel sector has smaller temperature than the ordinary one $T' \ll T$ [2]. On the other hand, once this condition is fulfilled, $B-L$ and CP violating interactions among ordinary and mirror particles can generate baryon asymmetries in both sectors [3], naturally giving the relation $\Omega'_B/\Omega_B \simeq 5$ between cosmological fractions of the dark and visible matter [4].

The same B or L violating interactions that lead to primordial baryogenesis can also induce mixing phenomena between the ordinary particles and their mirror partners. E.g. effective operator $(1/M)l\phi l'\phi'$ ($\Delta L = 1$) between the ordinary/mirror lepton and Higgs fields in the early universe gives rise to an efficient lepto-baryogenesis mechanism in both sectors, while at low energies it induces the mixing between ordinary (active) neutrinos $\nu_{e,\mu,\tau}$ and their mirror (sterile) partners $\nu'_{e,\mu,\tau}$ [5].

Effective six-fermion interaction $(1/M)^5(udd)(u'd'd')$ ($\Delta B = 1$) involving the ordinary (u, d) and mirror (u', d') quarks can provide an efficient baryogenesis mechanism at the scale M of few TeV which in addition can be testable at the LHC [6]. On the other hand, it induces the neutron−mirror neutron mixing, $\varepsilon(\bar{n}n' + \bar{n}'n)$. Since the masses of n and n' are exactly equal, in the vacuum conditions they must have a maximal mixing while the oscillation time $\tau_{nn'} = \varepsilon^{-1} \sim (M/10\,\text{TeV})^5$ s in their rest frame can be much smaller than the neutron β-decay time $\tau_\text{d} \simeq 880$ s; such a fast $n - n'$ oscillation is not excluded experimentally [6]. This seems rather surprising as it regards to the baryon number violating process ($\Delta B = 1$). The key moment is that for free neutrons $n - n'$ oscillation is suppressed by the Earth's magnetic field whereas it is ineffective for the neutrons bound in nuclei so that the nuclear destabilization limits become irrelevant.

In the last years several experiments searched for $n-n'$ oscillation via the magnetic field dependence of the neutron losses [7–9]. Note, however, that the lower bounds on $\tau_{nn'}$ reported by these experiments and adopted by the Particle Data Group [10] (the strongest limit reads $\tau_{nn'} > 414$ s [8]) become invalid if the Earth possesses a reasonably large mirror magnetic field: the latter cannot be screened in the experiments and can drastically change the probability of $n - n'$ oscillation [11]. On the other hand, if dark matter consists of mirror particles, it is also plausible that the solar system and the Earth itself may capture a significant amount of mirror matter due to feeble interactions between ordinary and mirror particles. The Earth's rotation gives rise to circular currents in the captured mirror matter which may induce a mirror magnetic field up to several Gauss [11].

In the presence of non-zero mirror field $\mathfrak{B}'$ the probability of $n - n'$ oscillation has a non-trivial dependence on the ordinary magnetic field $\mathfrak{B}$ and on its orientation relative to $\mathfrak{B}'$ [11]. In particular, for $\mathfrak{B}' \gtrsim 1$ G, the strongest bound comes from measurements of the neutron losses in the Earth's magnetic field which yield $\tau_{nn'}[\,\text{s}\,] \times \mathfrak{B}'[\,\text{G}\,] > 0.1$ [11, 12]. Thus, for $\mathfrak{B}' \sim 10$ G even $\tau_{nn'} \sim 10^{-2}$ s is allowed. Interestingly, such a fast $n-n'$ oscillation is not in conflict with the primordial nucleosynthesis or the neutron star stability bounds [6, 11]. In addition, anomalous dependence of the neutron losses on the magnetic field orientation observed in the experiment [9] can be interpreted in terms of $n - n'$ oscillation with $\tau_{nn'}$ of few seconds provided that $\mathfrak{B}' \simeq 0.1$ G [12].

In this letter we show that fast $n - n'$ oscillation can have intriguing implications for the propagation of ultrahigh-energy cosmic rays (UHECR). It brings to significant modifications of the spectrum at $E \gtrsim 10$ EeV which can be proved in future with better accuracy.

It is known that the cosmic microwave background (CMB) causes an abrupt end in the cosmic proton spectrum, the so called Greisen-Zatsepin-Kuzmin (GZK) cutoff [13]. The cutoff energy corresponds to the pion photoproduction threshold, $E_\text{GZK} = m_\pi m/2\varepsilon_\gamma \simeq 60$ EeV, where m and m_π are respectively the nucleon and pion masses and $\varepsilon_\gamma \simeq 3T \simeq 10^{-3}$ eV is an effective energy of relic photons, $T = 2.725$ K being the CMB temperature. The mean free path (m.f.p.) of the proton, $l_s \sim \langle\sigma(p\gamma \to N\pi)n_\gamma\rangle^{-1} \propto T^{-3}$, strongly depends on its energy. One has $l_s \sim 5$ Mpc for $E > 300$ EeV but it sharply increases at lower energies becoming $l_s > 100$ Mpc at $E < 60$ EeV. In each $p\gamma \to N\pi$ scattering the super-GZK protons lose about 20% of their energy.

The $p\gamma$-scattering has two main pion production channels, $p\gamma \to p\pi^0$ and $p\gamma \to n\pi^+$, with roughly comparable cross-sections. Conversion of the cosmic ray proton into the neutron does not influence the propagation length, since $n\gamma \to N\pi$ scatterings, $n\gamma \to n\pi^0$ $(p\pi^-)$, have nearly the same cross sections as $p\gamma \to N\pi$ ones. In addition the β-decay $n \to pe\tilde{\nu}_e$ converts the neutron back to the proton with practically the same energy. Up to $E \simeq 0.5$ ZeV the decay length $l_{\rm d} = \Gamma c\tau_{\rm d}$ ($\Gamma = E/m$ is Lorentz factor) is smaller than $n\gamma \to N\pi$ scattering length. Hence, cosmic ray carriers with $E \gg E_{\rm GZK}$ travel long distances transforming from protons to neutrons and back suffering significant energy losses which downgrade their energy to sub-GZK range. Yet, the baryon number in the cosmic ray propagation is conserved.

In presence of $n - n'$ oscillation the situation changes drastically: the produced neutron can now oscillate into a mirror one. If $\tau_{nn'} \ll \tau_{\rm d}$ the oscillation length $l_{\rm nn'} = c\Gamma\tau_{nn'}$ is much smaller than $l_{\rm d}$ and $l_{\rm s}$ so that at these scales oscillations may be averaged. The $n - n'$ transition probability reads [6, 11]

$$P(E) = \frac{1}{2[1 + (\Gamma\omega\tau_{nn'})^2]} = \frac{1}{2 + q(E/100\,{\rm EeV})^2}, \quad (1)$$

where $\omega = \frac{1}{2}|\mu_n \Delta\mathfrak{B}|$ and $\Delta\mathfrak{B} = \mathfrak{B} - \mathfrak{B}'$, μ_n being the neutron magnetic magnetic moment and $\mathfrak{B}$ and $\mathfrak{B}'$ being respectively the ordinary and mirror magnetic fields at the cosmological scales, or more precisely their transverse components. Factor $q = 0.45 \times (\tau_{nn'}/1{\rm s})^2 \times (\Delta\mathfrak{B}/1\ {\rm fG})^2$, shows the efficiency of $n - n'$ oscillation at $E \simeq E_{\rm GZK}$. Finally, β-decay of mirror neutron $n' \to p'e'\tilde{\nu}_e'$ converts a cosmic ray, being initially a proton, to a mirror proton.

The latter can be converted to ordinary proton via inverse chain of reactions: $p'\gamma' \to n'\pi'$ scattering, $n' - n$ transition and $n \to pe\tilde{\nu}_e$. However, the propagation length of mirror protons is much larger than that of ordinary ones, $l_s' \gg l_s$, as far as the temperature of mirror CMB is smaller than that of ordinary CMB, $T'/T = x \ll 1$. Namely, the Big Bang nucleosynthesis imposes a robust upper bound $x < 0.5$ or so [2], but the limits strengthen if one assumes that dark matter consists entirely of mirror baryons. In this case the large scale structure and CMB power spectrum require $x < 0.3$, while yet stronger limits $x < 0.2$ $(x < 0.1)$ arise by demanding that the Silk damping of mirror baryon perturbations does not prevent the formation of normal (dwarf) galaxies [2, 4].

For the relic mirror photon number density and their average energy we have $n_\gamma' = x^3 n_\gamma$ and $\varepsilon_\gamma' = x\varepsilon_\gamma$. Thus m.f.p. of mirror cosmic rays drastically amplifies, $l_{\rm s}' \simeq x^{-3} l_{\rm s}$, while the threshold energy of $p'\gamma' \to N'\pi'$ becomes, $E_{\rm GZK}' \simeq x^{-1} E_{\rm GZK}$. So, the energy range $E_{\rm GZK} \lesssim E \lesssim E_{\rm GZK}'$ acts for ordinary cosmic rays like a sink where they disappear – ordinary cosmic rays with $E > E_{\rm GZK}$ are converted to mirror ones, but the mirror ones may be converted (at much lower rate) to ordinary ones only at $E > E_{\rm GZK}'$. The dominant fraction of the cosmic rays produced in far distant sources must escape to the parallel sector via $n - n'$ oscillation. However, if there are powerful mirror sources the ordinary UHECR flux may be increased at $E > E_{\rm GZK}'$ by the contribution from cosmic rays arriving from the mirror sector.

In the presence of $n - n'$ oscillation, evolution of the four UHECR number densities $U_i = U_i(E, t)$, $i = p, n, p', n'$, in the expanding universe may be described by a system of coupled integro-differential equations

$$\begin{aligned} &\tfrac{\partial U_i}{\partial t} = Q_i - 3H(t)U_i + \tfrac{\partial[E(H(t)+\beta_i)U_i]}{\partial E} + \tfrac{mD_{ij}}{E\tau_{\rm d}}U_j \\ &-R_i(E,t)U_i + T_{ij}(E)\int_E^\infty d\tilde{E}\, W_{jk}(E,\tilde{E},t)U_k(\tilde{E},t), \end{aligned} \quad (2)$$

where $H(t)$ is Hubble parameter. We assume that cosmic rays sources are distributed homogeneously in space and their generation functions $Q_i(E, t)$ may have cosmological evolution with time t [14]. Here $W_{jk}(E, \tilde{E}, t))$ is the probability density for a nucleon k ($N = p, n$ or $N' = p', n'$) of energy $\tilde{E}$ to transform via its pion-production scatterings off the respective CMB (γ or γ') into a nucleon j (again N or N') with energy E. The matrix $T_{ij}(E)$, with $T_{pp} = T_{p'p'} = 1$, $T_{nn} = T_{n'n'} = 1 - P(E)$, $T_{nn'} = T_{n'n} = P(E)$ given by Eq. (1) and with other elements being zero, stands for transition probabilities due to $n - n'$ oscillation: the neutron n produced in $N\gamma$-scattering, $N = p, n$, promptly oscillates into n' with a probability $P(E)$ and vice versa; $R_i(E, t) = \int_0^E d\tilde{E} \sum_j W_{ji}(\tilde{E}, E, t)$ stands for probability of a nucleon i with energy E to disappears from the energy range dE; factors $\beta_{p,p'}(E, t)$ take into account the p and p' energy losses due to e^+e^- pair production ($\beta_{n,n'} = 0$). The matrix D_{ij} takes into account n and n' β-decays transforming neutrons back into protons with practically the same energy; here $D_{pn} = D_{p'n'} = 1$, $D_{nn} = D_{n'n'} = -1$ and all other elements are zero. In the absence of $n - n'$ oscillation the system (2) obviously splits into two independent sets of equations for ordinary and mirror cosmic rays.

At all reasonable energies neutrons decay before their $n\gamma \to N\pi$ scattering off CMB, so that $l_{\rm d} < l_{\rm s} \ll l_{\rm s}'$. The relation $l_{\rm d} \ll l_{\rm s}'$ holds very well for mirror neutrons, while for ordinary ones $l_{\rm d} < l_{\rm s}$ is fulfilled only at $E \lesssim 0.5$ ZeV. For this energy range the initial proton, after $p\gamma \to n\pi^+$ scattering, with following prompt $n - n'$ oscillation and neutron decay, instantly transforms into a mirror proton, $p \to p'$ with probability $P(E)$, and vice versa, $p' \to p$, neglecting the propagation periods when a nucleon dwells in the mixed $n - n'$ state. It should be noted that this approximation is perfect if the difference between $p\gamma$- and $n\gamma$-cross-sections is neglected. This allows to reduce the system of 4 equations (2) to a system of two equations

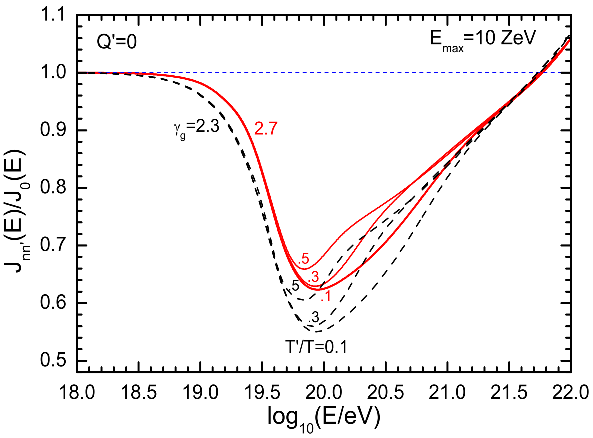

FIG. 1. Ratios of modified by $n - n'$ oscillation UHECR spectrum, $J_{nn'}(E)$, and "standard" spectrum, $J_0(E)$ (no oscillation), in the absence of mirror sources ($Q'(E) = 0$) and for different ratios of CMB temperatures $x = T'/T$. Source generation spectrum is taken as $Q(E) \propto E^{-\gamma_g}\Theta(E_{\max} - E)$.

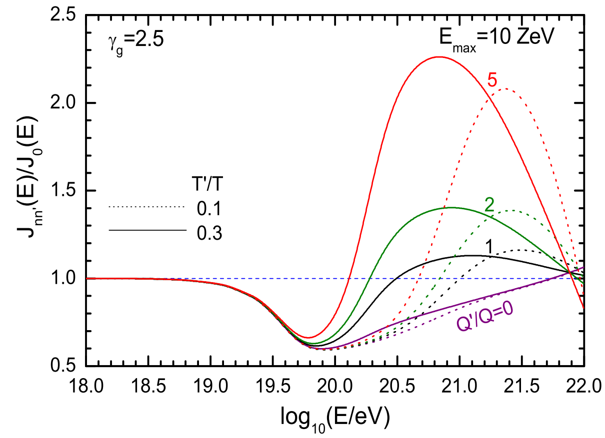

FIG. 2. The same as on Fig. 1 but in the presence of mirror sources, $Q'(E)$ with $\gamma_g = 2.5$, different ratios of source intensities, $Q'(E)/Q(E) = 0, 1, 2, 5$, and with $T'/T \leq 0.3$.

describing evolution of just p and p'.

To facilitate the calculations, the latter system of two integro-differential equations was reduced to an analog of a set of two coupled Fokker-Plank type differential equations by expanding the kernels of integrals in (2) in series at $\tilde{E} = E$ up to second derivatives. This method was proved to be valid by comparison with Monte Carlo simulations in the case of propagation of ordinary protons [15]. Moreover, we assume $q \ll 1$ in Eq. (1), so that $P(E) = 1/2$. This holds for $\Delta\mathfrak{B} \lesssim 1$ fG. The data concerning the cosmological magnetic fields are controversial and there are some hints that they may be larger. However, at large scales ordinary and mirror magnetic fields can be strongly correlated, so that their difference is vanishing [6]. There is also a possibility of the resonance MSW like transitions if magnetic fields have turbulent structure at scales less than 1 Mpc.

The results of our calculations for different sets of parameters are shown in Fig. 1 and Fig. 2. Let us first discuss the case when there are no mirror cosmic rays sources, $Q' = 0$. Then cosmic rays with $E > E_{\rm GZK}$ produced in distant extragalactic sources not only lose their energy during propagation, but also degrade in number owing to $n - n'$ transition. This makes the cutoff in the cosmic ray spectrum to begin at energies lower than $E_{\rm GZK} \simeq 60$ EeV. Now the cutoff relates also to the non-conservation of the baryon number B: the most part of initial protons transforms into mirror protons, thus getting invisible. On the other hand, an imaginary mirror observer would detect a flux of mirror protons with energies $E > E_{\rm GZK}$ originated in our world. In other words, the baryon numbers B and B' are not conserved individually, but the sum $B + B'$ must be conserved.

In the Fig. 1 we show the modification factor $\eta(E) = J_{nn'}(E)/J_0(E)$, defined as the ratio of UHECR spectra calculated with and without $n - n'$ oscillation, in the absence of mirror sources, $Q' = 0$. Actually, it has an almost universal shape just weakly depending both on the source generation function index γ_g and on the ratio of CMB temperatures $x = T'/T$ in two sectors. Really, the spectrum cutoff with oscillation starts earlier, at $E \sim 10$ EeV, while the maximal difference from the GZK prediction (about 40%) is reached around 100 EeV.

Fig. 2 shows the same spectral modification factor $\eta(E)$ in the presence of the mirror sources, for different values of $Q'(E)/Q(E)$. In fact, if mirror baryons constitute dark matter, i.e. Ω'_B/Ω_B, one can expect that there are also mirror cosmic rays. In fact, in quasars and AGN the central black holes can be a potential sites for acceleration of both ordinary and mirror protons. Therefore, it is natural to assume that the ratio $Q'(E)/Q(E)$ is the same as the ratio of the relative matter fractions, Ω'_B/Ω_B. Let us recall, that $\Omega'_B/\Omega_B \sim 5$ can be naturally achieved in the joint ordinary-mirror baryogenesis mechanism [3] provided that $x < 0.3$ or so [4].

In this case, in spite of larger m.f.p., the mirror cosmic rays can partially move to the ordinary sector and substantially increase the UHECR flux at energies above $E = 100$ EeV. The value of the turning point depends on the parameter $x = T'/T$ as well as on the strength of mirror sources, $Q'(E)/Q(E)$. Note however that the existence and position of the pre-GZK cutoff is robust: the shape of the $\eta(E)$ at $E = 10 - 100$ EeV practically does not depend on the strength of the mirror sources.

Unfortunately, the data statistics achieved at the operating installations is not yet enough to determine the exact shape of the spectrum above 100 EeV. However, the earlier end of the cosmic ray spectrum seems to be indicated by the data of PAO [16]. A controversy between the Auger and HiRes [17] - TA [18] data concerning the shape and chemical composition of the UHECR spectrum is not yet resolved (see e.g. [19]). Auger sees the cutoff starting from $E \simeq 25$ EeV, a factor of 2 lower than $E_{\rm GZK}$ and claims to see here heavy nuclei. The estimated systematic uncertainty of 22% is not sufficient for adjusting the cutoff position. The HiRes data indicate cosmic rays to be protons with cutoff at $E_{\rm GZK}$, but their statistic is lower. It is worth to note, however, that the issue of the composition determining at such high energies is a subject of theoretical models rather than of experimentally measured cross-section and multiplicities (see e.g. [20]). The proposed $n - n'$ oscillation model mitigates the controversy in the data of two experiments putting the beginning of the cutoff in the middle, though extragalactic protons are assumed to be cosmic ray carriers. It should be noted, that in case the UHECR are mostly heavy nuclei, the neutrons produced in their photodisintegration on CMB will be also lost as they escape to the parallel world.

Prompt neutron oscillations may provide correlation of cosmic rays with $E > 100$ EeV with distant sources (e.g. BL Lacs [21]) as an indication of the UHECR transport in the parallel world. It is interesting to remark, that cosmic ray fraction which comes from the parallel sector, can be composed by anti-protons rather than by protons.

Another immediate consequence of the baryon losses due $n - n'$ transitions is a strong suppression of the cosmogenic Berezinsky-Zatsepin (BZ) [22] neutrino flux mostly produced via $p\gamma \to n\pi^+$ scattering with following $\pi^+ \to \mu^+\nu_\mu$ and $\mu^+ \to e^+\nu_e\bar{\nu}_\mu$ decays. This conclusion remains pessimistic even if ordinary and mirror neutrinos also have non-zero mixing [5]. Really, since $T' < T$, mirror cosmic rays have very large m.f.p., $l'_s \sim x^{-3} l_s$ (e.g. $l'_s \sim 600$ Mpc for $x = 0.2$ versus $l_s \sim 5$ Mpc), and thus suffer much less scatterings than ordinary ones. Therefore the diffuse cosmogenic neutrino flux may turn out to be much lower than expected [23]. Even the giant ICECUBE [24] with its control over 1 km^3 of ice may be insufficient to detect this flux.

The electromagnetic cascades originated from $p\gamma \to p\pi^0$ channel with subsequent $\pi^0 \to 2\gamma$ decay and $\gamma\gamma_{\rm CMB} \to e^+e^-$ will be also suppressed, since most amount of the ordinary super-GZK cosmic rays escape to the parallel world just after few proton scatterings off CMB. This reduces the restrictions imposed on the UHECR models by the diffuse extragalactic gamma-ray flux measured by Fermi-LAT [25] at $E \gtrsim 100$ GeV [23].

To conclude, the interesting effect of the fast baryon number violation via $n-n'$ oscillation may be detected in the laboratory neutron disappearence and regeneration experiments, while the underlying TeV-scale physics can be tested at the LHC [6]. Here we show that this attractive concept may complementary bring to the testable modifications of the cosmic ray spectrum. Due to the baryon non-conservation during the UHECR propagation the cutoff of the spectrum shifts to lower energies and becomes significantly steeper. On the other hand, in the presence of powerful mirror sources the observed spectrum at highest energies may get even higher as compared to the 'no oscillation' case.

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