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Neutrons and antiprotons in ultrahigh-energy cosmic rays

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Abstract. The neutron fraction in the very high-energy cosmic rays near the Greisen-Zatsepin-Kuzmin (GZK) cutoff energy is analyzed by taking into account the time dilation effect of the neutron decays and also the pion photoproduction behaviors above the GZK cutoff. We predict a non-trivial neutron fraction above the GZK cutoff and a negligibly small neutron fraction below. However, there should be a large antiproton fraction in the high-energy cosmic rays below the GZK cutoff in several existing models for the observed cosmic-ray events above and near the GZK cutoff. Such a large antiproton fraction can manifest itself by the muon charge ratio μ^+/μ^- in the collisions of the primary nucleon cosmic rays with the atmosphere, if there is no neutron contribution. We suggest to use the muon charge ratio as one of the information to detect the composition of the primary cosmic rays near or below the GZK cutoff.

PACS. 98.70.Sa Cosmic rays (including sources, origin, acceleration, and interactions) – 03.30.+p Special relativity – 13.85.Tp Cosmic-ray interactions – 98.70.Vc Background radiations

The observation of ultrahigh-energy cosmic rays above and near the Greisen-Zatsepin-Kuzmin (GZK) cutoff energy presents an outstanding puzzle in astrophysics and cosmology [1]. It has long been anticipated that the highest-energy cosmic rays would be protons from outside the galaxy, and there is an upper limit of the highest energy in the observed proton spectrum, commonly referred to as the GZK cutoff [2], as the protons travelling from intergalactic distances should experience energy losses owing to pion productions by the photons in the cosmic background radiation. Then, it is suggested [3] that the particles with energy above the GZK cutoff must be coming from within the local "supercluster" of galaxies of which we are a part. Thus, the "GZK cutoff" is not a true cutoff, but a suppression of the ultrahigh-energy cosmic-ray flux owing to a limitation of the propagation distance, which we refer to as the GZK zone. Although there have been some novel explanations for the observed cosmic-ray events above the GZK cutoff, it is natural to expect that these ultrahigh-energy cosmic rays come from sources within the GZK zone, *i.e.*, not far from us in more than tens of Mpc. The "Z-bursts" [4–6] can explain the highest-energy cosmic-ray events, with sources within the GZK zone [3]. The reason is that the "Z-bursts" are from the Z-boson annihilations of the ultrahigh-energy neutrino (antineutrino) cosmic rays with the relic neutrinos (antineutrinos) in the cosmic background radiation, and these annihilations can happen anywhere in the universe. The "Z-bursts" can produce nucleon cosmic rays with ultrahigh energy within the GZK zone, as the energy of the produced Z-bosons is high enough by the collision of ultrahigh-energy neutrino beams with the relic neutrinos of non-zero mass. Therefore, the nucleons with ultrahigh energy from "Z-bursts" can reach us without the GZK constraint, and this can explain the observed cosmic-ray events with energy above and near the GZK cutoff. Several existing models of similar kinds, such as using relic metastable superheavy particles [7] and topological defects [8] as origins of ultrahigh-energy particles, can also explain the ultrahigh-energy cosmic-ray events above and near the GZK cutoff.

In fact, these models can produce a number of photons and nucleons to reach the Earth; for example, the photon/nucleon ratio is about 10 on average in the Z-burst model. A possible method to test these models is by the large γ/p ratio for the cosmic rays near the upper end of the spectrum. This can be achieved by the separation of primary photon and proton cosmic-ray events with different characteristic air shower profiles. However, for the nucleon cosmic rays from these models, there could be a sizable number of neutrons and antinucleons in comparison with that of the protons. For example, there are roughly equal numbers of protons and neutrons at the source point in the Z-burst model, with also a symmetric part of antinucleons. Therefore, it is necessary to estimate

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the composition of the nucleon cosmic rays. We will study the role played by the neutrons in the ultrahigh-energy cosmic rays near the GZK cutoff. We will take into account the time dilation effect of the neutron decays and the pion photoproduction behaviors of the nucleons above the GZK cutoff. It will be shown that there should be a non-trivial fraction of neutrons above the GZK cutoff, whereas the neutron fraction is negligibly small below the GZK cutoff. Since there should be equal numbers of protons and antiprotons in the cosmic rays from the Z-bursts, and these protons and antiprotons will produce different muon charge ratio μ^+/μ^- in the air showers, we thus suggest to measure the μ^+/μ^- ratio of the air showers by the primary cosmic rays near or below the GZK cutoff, as one of the information to detect the composition of the primary cosmic rays with high energy.

The 2.73 K cosmic microwave background (CMB) of the photons satisfies Planck's ideal black-body radiation formula, with the number density $n_\gamma = 16\pi\zeta(3)$ $(kT/hc)^3 = 413$ photons per cm^3 and the mean energy per photon $\epsilon_\gamma = \pi^4 kT/30\zeta(3) = 6.35\times10^{-4}$ eV, where $\zeta(3) = 1.20$ is the Riemann Zeta function. When the nucleon with 4-momentum $p = (E, \mathbf{p})$ interacts with the photon with 4-momentum $k = (\epsilon, \mathbf{k})$, and composes into a system with the center-of-mass energy squared S, we have

$$E = \left(S - m_N^2\right)/2\epsilon\left(1 - \sqrt{1 - m_N^2/E^2}\cos\theta\right), \tag{1}$$

where θ is the angle between $\mathbf{p}$ and $\mathbf{k}$. θ cannot be zero since a nucleon cannot catch up a photon moving in the same direction, and the energy of the nucleon E must be very large near the pion photoproduction process $N + \gamma_{\mathrm{CMB}} \to \pi + N$, therefore we have,

$$E \approx \left(S - m_N^2\right)/2\epsilon\,(1 - \cos\theta)\,. \tag{2}$$

The threshold energy for pion production $N + \gamma_{\mathrm{CMB}} \to \pi + N$ is

$$E \approx \left(2m_N m_\pi + m_\pi^2\right)/4\epsilon = 1.10\times10^{20}\ \mathrm{eV}, \tag{3}$$

and the threshold energy for producing the Δ-resonance $N + \gamma_{\mathrm{CMB}} \to \Delta \to \pi + N$ is

$$E \approx \left(m_\Delta^2 - m_N^2\right)/4\epsilon = 2.52\times10^{20}\ \mathrm{eV}. \tag{4}$$

The neutron has a mean lifetime $\tau_n = 887$ s in its rest reference frame. Due to the time dilation effect of the special relativity, the lifetime of a moving particle is dilated by a factor $\gamma_n = E_n/m_n$. Therefore, the mean free path that a moving neutron can travel before its beta-decay into the proton should be, for a neutron at the pion production threshold,

$$l_n \approx c\gamma_n\tau_n = 3.12\times10^{24}\ \mathrm{cm} = 1.01\ \mathrm{Mpc}, \tag{5}$$

and for a neutron at the Δ-resonance threshold,

$$l_n \approx c\gamma_n\tau_n = 7.11\times10^{24}\ \mathrm{cm} = 2.30\ \mathrm{Mpc}. \tag{6}$$

Therefore, the neutron fraction around the GZK cutoff is expected to be negligibly small for nucleons coming from a source with distance of considerably more than a few Mpc, if we only consider the time dilation effect of the neutrons.

However, the situation is different if we take into account the detailed features for the pion photoproduction $N + \gamma_{\mathrm{CMB}} \to \pi + N$, which, when distinguishing between proton and neutron, should be written as $p + \gamma_{\mathrm{CMB}} \to \pi^+ + n$, $n + \gamma_{\mathrm{CMB}} \to \pi^- + p$, $p + \gamma_{\mathrm{CMB}} \to \pi^0 + p$, and $n + \gamma_{\mathrm{CMB}} \to \pi^0 + n$. These four processes have quite different cross-sections, as can be understood from the low-energy theorem [9] as well as from the chiral quark model [10]. Roughly speaking, the cross-section of the pion photoproduction $N(\gamma,\pi)N$ is proportional to A^2 with the four physical amplitudes of A expressed by [10],

$$A(p\gamma \to \pi^+ n) = \sqrt{2}\left(A^- + A^0\right), \tag{7}$$

$$A(n\gamma \to \pi^- p) = \sqrt{2}\left(A^- - A^0\right), \tag{8}$$

$$A(p\gamma \to \pi^0 p) = A^+ + A^0, \tag{9}$$

$$A(n\gamma \to \pi^0 n) = A^+ - A^0, \tag{10}$$

where the isospin amplitudes can be expanded in terms of the ratio between pion mass and nucleon mass $\eta = m_\pi/m_N$,

$$A^- = 1 + O(\eta^2), \quad A^+ = A^0 = -\eta/2 + O(\eta^2). \tag{11}$$

Thus, we get

$$\frac{\sigma(n\gamma \to \pi^- p)}{\sigma(p\gamma \to \pi^+ n)} = \frac{(1+\eta/2)^2}{(1-\eta/2)^2} \approx 1.34, \tag{12}$$

which is in excellent agreement with the experimental data [11], and

$$\frac{\sigma(p\gamma \to \pi^0 p)}{\sigma(p\gamma \to \pi^+ n)} = \frac{\eta^2}{2(1-\eta/2)^2} \approx 0.01, \tag{13}$$

$$\frac{\sigma(n\gamma \to \pi^0 n)}{\sigma(p\gamma \to \pi^+ n)} = \frac{O(\eta^4)}{2(1-\eta/2)^2} \approx O(\eta^4), \tag{14}$$

which means that the neutral-pion production processes, $p + \gamma_{\mathrm{CMB}} \to \pi^0 + p$ and $n + \gamma_{\mathrm{CMB}} \to \pi^0 + n$, can be neglected. Adopting an average cross-section $\sigma(p\gamma \to \pi^+ n) = 200$ μb [2,3] above the pion photoproduction threshold, we have the mean free path of interaction for the proton

$$\lambda_p = \frac{1}{n_\gamma\sigma(p\gamma \to \pi^+ n)} = 1.21\times10^{25}\ \mathrm{cm} = 3.92\ \mathrm{Mpc}, \tag{15}$$

and that for the neutron

$$\lambda_n = \frac{1}{n_\gamma\sigma(n\gamma \to \pi^- p)} = 9.04\times10^{24}\ \mathrm{cm} = 2.93\ \mathrm{Mpc}. \tag{16}$$

It is interesting to notice that the protons and neutrons change into each other via charged pion production by the relic photons in the travel until the nucleon energies degraded to below the GZK cutoff. There is always a certain amount of neutron fraction for nucleons above the pion photoproduction threshold, since the protons can always change into neutrons via the charged-pion photoproduction. Though the neutrons change faster into protons via both beta-decay or charged-pion photoproduction (with effective mean free path $\lambda_n^{\rm eff} = l_n\lambda_n/(l_n + \lambda_n)$), these produced protons continue to change into neutrons if their energy is still above the pion production threshold. As a consequence, there is always a non-trivial neutron fraction in the nucleon cosmic rays above the GZK cutoff. The magnitude of the neutron fraction depends on the energy of the nucleon and the sources, and it increases with the increase of energy, as the time dilation effect is stronger for neutrons with higher energy. Detailed features of the neutron fraction and nucleon spectrum may also provide information on the sources of the nucleon cosmic rays, such as their distance, the nucleon spectrum of the initial sources and their neutron/proton ratios. For example, assuming that the nucleons with energy above the GZK cutoff are from a point source with a uniform nucleon spectrum (*i.e.*, with a constant value of density distribution) at a distance far away (explicit calculation shows that $3\lambda_p$ is enough), the neutron/proton ratio should reach the equilibrium value of $\lambda_n^{\rm eff}/\lambda_p \approx 0.19$ at the pion production threshold and 0.33 at the Δ production threshold, independently of the neutron/proton ratio of the source. Adopting a small cross-section at threshold could reduce $\lambda_n^{\rm eff}/\lambda_p$ to around 0.05, in agreement with explicit model calculations [12]. Thus, there must be a significant neutron fraction in the nucleon cosmic rays above the GZK cutoff, even if the sources only emit protons.

However, the neutron fraction is negligibly small below the GZK cutoff, since only the neutrons within a distance comparable to the mean free path of decay $l_n \approx 1$ Mpc can reach the Earth. The protons with energy below the GZK cutoff may interact with the relic photons via electron-position pair production, but the energy loss is small, of only 0.1% compared to 20% for pion production. Therefore, such protons may come from any source with distance within half the Hubble length [2]. We thus expect a small neutron/proton ratio below the GZK cutoff.

For the Z-bursts of particle productions, there should be a symmetry between the nucleon and antinucleon productions in the standard model. Thus, there should be equal numbers of protons and antiprotons in the nucleon cosmic rays from the Z-bursts. Balloon and satellite investigations can provide direct measurements of the cosmic rays of proton and antiprotons, respectively. Unfortunately, the available measurements can only reach to the energy scale of 10^{15} eV [13], still $4 \to 5$ orders below the energy region for our purpose. One of the methods to identify the hadron species in the cosmic rays is by measuring the muon charge ratio μ^+/μ^- of the air shower by the primary cosmic rays. It has been known that the μ^+/μ^- ratio may provide information on the neutron/proton ratio in the primary cosmic rays [14]. With the improvements in the knowledge of particle productions in hadron-hadron interactions from accelerator experiments and also in the understanding of particle production and propagation mechanism in the atmosphere, the μ^+/μ^- ratio, in combination with other coincidence measurements, can reveal the species in the primary beams. However, we will show that the μ^+/μ^- ratio should be similar for primary neutron and antiproton beams. Thus, the μ^+/μ^- ratio is hard to distinguish between the neutron and antiproton in the nucleon cosmic rays. With the above prediction that the neutron fraction is negligibly small below the GZK cutoff, we suggest to use the μ^+/μ^- ratio as a measurement of the antiproton fraction in the cosmic rays below the GZK cutoff.

In fact, the muons in the air showers are mainly from decays of pions and kaons produced in the interactions of the primary cosmic rays with the atmosphere [14,15]. The very high-energy secondary pion and kaon cosmic rays can be considered as from the current fragmentation of partons in deep inelastic scattering of the primary cosmic rays with the nucleon targets of the atmosphere in a first approximation [16]. We also consider only the favored fragmentation processes, *i.e.*, the π^+, which is composed of valence u and $\overline{d}$ quarks, is from the fragmentation of u and $\overline{d}$ quarks in the nucleon beam, and the π^-, which is composed of valence $\overline{u}$ and d quarks, is from the fragmentation of $\overline{u}$ and d quarks [17]. Similarly, the K^+, which is composed of valence u and $\overline{s}$, is from the fragmentation of u and $\overline{s}$ quarks, and the K^-, which is composed of valence $\overline{u}$ and s, is from the fragmentation of $\overline{u}$ and s quarks. The μ^+ is from the decay of a π^+ or a K^+ and the μ^- is from the decay of a π^- or a K^-. We can roughly estimate the muon charge ratio by

$$\frac{\mu^+}{\mu^-} = \frac{\int_0^1 \mathrm{d}x \left\{ \left[u(x) + \overline{d}(x)\right] + \kappa \left[u(x) + \overline{s}(x)\right] \right\}}{\int_0^1 \mathrm{d}x \left\{ \left[d(x) + \overline{u}(x)\right] + \kappa \left[\overline{u}(x) + s(x)\right] \right\}}, \qquad (17)$$

where $q(x)$ is the quark distribution with flavor q for the incident hadron beam and $\kappa \sim 0.1 \to 0.3$ is a factor reflecting the relative muon flux and fragmentation behavior of K/π. Secondary collisions do not influence the above estimation but can significantly reduce the final detected muon energies, since the current parton beams still keep their flavor content and act as the current partons after the strong interactions with the partons in the atmosphere targets. Adopting a simple model estimation of the parton flavor content in the nucleon without any parameter [18], we find that $\mu^+/\mu^- \sim 1.7$ for the proton and $\mu^+/\mu^- \sim 0.7$ for the neutron. This simple evaluation is in agreement with the empirical expectation of $\mu^+/\mu^- \approx 1.66$ for the proton and $\mu^+/\mu^- \approx 0.695$ for the neutron [14] as well as with that in an extensive Monte Carlo calculation [19]; thus it provides a clear picture to understand the dominant features for the muon charge ratio by the primary hadronic cosmic rays. As to the μ^+/μ^- ratio for the antiproton, it is equivalent to the μ^-/μ^+ ratio for the proton by using eq. (17); thus we find $\mu^+/\mu^- \sim 0.6$ for the antiproton, which is close to that for the neutron. The μ^+/μ^- ratio for the antineutron is also equivalent to the μ^-/μ^+ ratio for the neutron, and it is $\mu^+/\mu^- \sim 1.4$, which is close to that for the proton. It is hard to distinguish between the primary neutrons and antiprotons (or protons and antineutrons) by the μ^+/μ^- ratio of the air shower, unless a very high-precision measurement is performed and also our knowledge of the muon charge ratio for each nucleon species is well established.

For the nucleon cosmic rays with energy above the pion photoproduction, there is an admixture of neutrons and antinucleons with the protons. It is hard to make a clear distinction between the neutron and antiproton (proton and antineutron) by the muon charge ratio μ^+/μ^-. Also the number of nucleons should be very limited by the GZK cutoff suppression. But there will be only protons and antiprotons in the cosmic rays below the GZK cutoff from our above discussion. With the collection of a sizeable number of events with enough statistics, we expect to detect the antiproton content in the cosmic rays by the measurement of the μ^+/μ^- ratio. The difference in the muon charge ratios between protons and antiprotons will be enhanced if there is an energy cut on the detected muons, as the ratio $\left[u(x)+\overline{d}(x)\right]/\left[d(x)+\overline{u}(x)\right]$ (*i.e.*, the dominant contribution in eq. (17)) has a strong x dependence to increase for proton and decrease for antiproton at large x. There could be also a composition of heavy nuclei in the ultrahigh-energy cosmic rays [20]. The nucleus beams are estimated, by using eq. (17), to have the muon charge ratio $\mu^+/\mu^- \approx 1.1$, which is different from both of those for protons and antiprotons. However, methods have been developed to identify the primary nucleon and nuclei by other information such as Čerenkov radiation [21]. Secondary muon size distributions have been also used in available experiments to identify the mass composition of primary-cosmic-ray extensive air showers [22,23]. We suggest to add the muon charge as further information to identify the antiproton composition. In combination with other information, it is thus possible to detect the hadronic composition by measuring the muon charge ratio for the cosmic-ray events with ultrahigh energy.

We need to point out here that none of the available facilities for ultrahigh-energy cosmic rays is aimed at measuring the muon charge ratio as its objective goal, so it is not practical to expect the measurement of the muon charge ratio for the ultrahigh-energy comic-ray showers within a short period. In principle, there should be no difficulty to measure the muon charge ratio by the available techniques of detectors [24], but this feature needs to be incorporated into the design of new-generation facilities for the physical goal we suggested. It is also not practical to measure the muon charge ratio on an event-by-event basis. The reason is that not all particles in an ultrahigh-energy cosmic shower can be detected: the detectors are distributed in arrays, and cannot cover the whole region. So some muons should be lost in the detection procedures. Therefore, the muon charge ratio should be studied from a large number of events in the sense of statistics. Also for our goal of identifying the nucleon species by their muon charge ratio, the muons should be detected at distances near the cores of the cosmic-ray showers, and the energy of the muons should be high enough to guarantee the detected muons of being from the cascading fragmentation of the current partons in the primary cosmic rays in consequent multi-scattering processes. We should point out that there are technical limitations of the highest energy of muons to be detected, so we should not expect that the detected muons are from the the first fragmentation of the partons in the primary cosmic rays, but rather the current partons in the primary cosmic rays should still keep at the leading current partons in the subsequent scattering processes, so that their flavor information is not completely lost at the highest energy of muons to be detected[1]. We should also point out that the flavor structure of the partons is not explicitly included in the available Monte Carlo simulations, as the physics picture of the current fragmentation we described above has not been incorporated in the available Monte Carlo codes or models. Similarly to the available air shower profiles with muon size distributions [22], detailed features with also muon charge and energy distributions for the air shower profiles of primary proton and antiproton cosmic rays are needed and waiting to be constructed by further explicit researches. This can be only realized by new-generation experiments aiming at detecting the antiproton content in the cosmic rays, by collections of a large number of events of cosmic-ray showers, together with their detailed muon charge and energy information (perhaps with also orientation distribution in the Earth's magnetic field) contained in the measurements.

Our results not only work for the Z-burst hypothesis, they also apply to any model involving the neutron and antiproton contents in the cosmic rays. The cosmic rays above and the GZK cutoff can be attributed as originated from the decays of relic metastable superheavy particles clustered as dark matter in the galactic halo [7], or from the topological defects that are left over from the early-universe phase transitions caused by the spontaneous breaking of symmetries [8]. There should be also some composition of neutrons and antinucleons in the cosmic rays in these models. In fact, the role played by the time dilation effect of the neutrons has been discussed in a number of papers [4,25]. But the combination with the proton/neutron changing properties in their propagation makes this dilation effect more significant. We thus obtain the interesting scenario in which the proton and neutron with energy above the GZK cutoff interchange between each other upon interaction with the relic photons in their propagation, and this indicates a non-trivial neutron fraction in the nucleon cosmic rays above the GZK cutoff. Our prediction of the propagation of neutrons and the suggestion of using the muon charge ratio to detect the antiproton fraction of the cosmic rays below the GZK cutoff, are applicable to all these models.

In summary, we studied the role of neutrons in the cosmic rays by taking into account the time dilation effect and the proton/neutron changing properties in the pion photoproduction by the relic photons. We predict a non-trivial neutron fraction in the cosmic rays above the GZK cutoff, no matter if the nucleon cosmic rays come from sources with distance comparable to the GZK zone or within local

[1] Or the muon detector should be placed deep underground for the purpose to detect the muons with initially very high energy.

galaxies. However, there is a negligibly small neutron fraction in the cosmic rays with energy below the GZK cutoff, unless the sources are with distance comparable to 1 Mpc. Thus, we also suggest to use the muon charge ratio to detect the antiproton content of the cosmic rays below the GZK cutoff. This may serve to provide some more information concerning several existing models using Z-bursts, superheavy particles, and topological defects as origins for the observed events of cosmic rays with energy above and near the GZK cutoff.

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