Unstable Superheavy Relic Particles as a Source of Neutrinos Responsible for Ultrahigh-Energy Cosmic Rays

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Decays of superheavy relic particles may produce extremely energetic neutrinos. Their annihilations on the relic neutrinos can be the origin of the cosmic rays with energies beyond the Greisen-Zatsepin-Kuzmin cutoff. The redshift acts as a cosmological filter selecting the sources at some particular value $z_e \pm \delta z$, for which the present neutrino energy is close to the Z pole of the annihilation cross section. We predict no directional correlation of the ultrahigh-energy cosmic rays with the galactic halo. At the same time, there can be some directional correlations in the data, reflecting the distribution of matter at redshift $z = z_e \pm \delta z$. Both of these features are manifest in the existing data. Our scenario is consistent with the neutrino mass reported by super-Kamiokande and requires no lepton asymmetry or clustering of the background neutrinos.

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Cosmic rays [1] with energies beyond the Greisen-Zatsepin-Kuzmin (GZK) cutoff [2] present a challenging outstanding puzzle in astroparticle physics and cosmology. One of the most appealing and economical explanations, proposed by Weiler [3], is based on the observation that the GZK cutoff is absent for neutrinos [3,4]. High-energy neutrinos can annihilate near to Earth on the background relic neutrinos via the Z resonance [3] producing the ultrahigh-energy cosmic rays (UHECR). A very appealing feature of this scenario is that the requisite energy scale appears naturally [5] if the relic neutrinos have mass $m_\nu = m_{\rm SK} \equiv 0.07^{+0.02}_{-0.04}$ eV, as inferred from the super-Kamiokande (SK) data (assuming no degeneracy in the neutrino mass spectrum). Such relic neutrinos can efficiently annihilate a neutrino with energy $E_\nu = M_Z^2/2m_{\rm SK} \sim 10^{23}$ eV, corresponding to a Z resonance. This energy happens to be just a few orders of magnitude above the GZK cutoff, which is precisely what is needed to explain the GZK puzzle.

The only problematic element in this scenario [3,5] so far is the source of the ultrahigh-energy neutrinos. In this paper we show that heavy unstable relic particles can produce the requisite neutrinos. The spectrum of these neutrinos is different from that of known astrophysical neutrino sources (it grows rapidly with energy, up to a sharp cutoff), so that the upper bounds of Ref. [6] do not apply. The flux of ultrahigh-energy neutrinos may be high enough to explain UHECR regardless of the lepton asymmetry.

Heavy relic particles decaying into hadrons and photons have been considered as sources of UHECR [7–9]. However, the lack of directional correlation of the observed events with the galactic halo and the observed clustering of events [10] in the directions unrelated to the distribution of the galactic dark matter may stymie this explanation. Indeed, if the decaying particles are the origin of the ultrahigh-energy protons and photons, one expects the directions of UHECR to point to some nearby sources. The present data are too sparse to reach a definite conclusion [11].

If, however, the superheavy relic particles decay into neutrinos, the directional correlation with the local distribution of matter is not expected in general. The only significant contribution to the $\nu\bar{\nu}$ annihilation ($\nu\bar{\nu} \to Z \to p\gamma\ldots$) on background neutrinos with mass m_ν comes from energies near the Z pole, so the high-energy neutrino must have energy close to $E_{\rm res} = M_Z^2/2m_\nu$ to produce an appreciable amount of cosmic rays. Let us suppose that the ultrahigh-energy neutrinos come from a two-body decay of some superheavy particle X into a neutrino and some other light particle. If the mass of the relic particle m_X is not fine-tuned to be exactly $2E_{\rm res}$, the local distribution of X particles has no effect on the highest-energy cosmic rays. If $m_X > 2E_{\rm res}$, the neutrinos produced at redshift $z_e = (m_X/2E_{\rm res} - 1)$ annihilate very efficiently close to Earth because their present energy corresponds to the Z pole. The redshift acts as a cosmological filter selecting the sources at some particular value z_e. The directions of the UHECR should, therefore, point to sources at $z = z_e$, not to those in the local group. One may still observe clustering of events congenial to the distribution of luminous matter at $z \approx z_e$, but not at $z \approx 0$.

Let us consider some superheavy relic particle X that can presently contribute to the cold dark matter [8,12]. Such particles could, for example, be produced nonthermally at preheating [9]. Let us also assume that it has a lifetime τ_X that is much greater than the age of the universe t_0 and that it decays with emission of at least one neutrino with branching ratio B_ν. We assume that hadronic and other visible decay modes have a negligible branching ratio. For simplicity, we will consider a two-body decay with emission of a neutrino with energy $E_{\nu,e} = m_X/2$. Generalizations to many-body processes and other modes of decay are straightforward.

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The spectrum of ultrahigh-energy neutrinos from decaying unstable heavy particles is given by [13,14]

$$E\,\frac{d\phi}{dE} = \frac{3}{2}\,\phi_{\gamma,0} Y_{X,0} B_\nu\,\frac{t_0}{\tau_X}\left(\frac{E}{m_X/2}\right)^{3/2}\theta\left(\frac{m_X}{2} - E\right), \tag{1}$$

where we have assumed $\tau_X \gg t_0$. Here $\phi_{\gamma,0} = n_{\gamma,0}/4\pi \approx 10^{12}\ \mathrm{cm^{-2}\,s^{-1}\,sr^{-1}}$ is the flux of the cosmic microwave background photons, and $Y_{X,0}$ is the ratio of the X number density to that of photons, $Y_{X,0} = n_{X,0}/n_{\gamma,0}$. We assume that the Universe is matter dominated from the time of emission until the present. As usual, index 0 refers to the present time, while subscript e denotes the time of emission.

We will now compute the flux of UHECR from the annihilation of ultrahigh-energy neutrinos on the background neutrinos with mass m_ν. The cross section for the process $\nu\bar{\nu} \to Z^* \to$ hadrons has a sharp maximum at the Z pole: $\sigma \propto 1/\{(s - M_Z^2)^2 + M_Z^2\Gamma_Z^2\}$, where $s = 2E_\nu m_\nu$, and $\Gamma_Z \approx 2.49$ GeV is the Z width. We are interested in the neutrino annihilations within the attenuation length of protons and photons, which is about 50 Mpc from Earth. Within this radius, one can neglect the redshift. Only those neutrinos that have energies $E_{\nu,0} = E_{\mathrm{res}} \pm \delta E = (M_Z^2/2m_\nu)[1 \pm \Gamma_Z/M_Z]$ can contribute to the flux of UHECR. The flux $\Delta\phi$ of these neutrinos can be obtained by integrating $d\phi(E)/dE$ in Eq. (1) from $E_{\mathrm{res}} - \delta E$ to $E_{\mathrm{res}} + \delta E$:

$$\Delta\phi = 3\phi_{\gamma,0} Y_{X,0} B_\nu\,\frac{t_0}{\tau_X}\left(\frac{E_{\mathrm{res}}}{m_X/2}\right)^{3/2}\left(\frac{\Gamma_Z}{M_Z}\right). \tag{2}$$

The value of $n_{X,0} = \Omega_X \rho_c/m_X$ is bounded from above by the requirement that $\Omega_X h^2 < 0.25$. X particles can be the cold dark matter [8,12] if $\Omega_X h^2 \approx 0.1$–0.25.

The probability P for each of these neutrinos to interact inside the GZK sphere, that is, within 50 Mpc from Earth, depends on the lepton asymmetry parameter $\eta = n_{\nu,\mathrm{relic}}/n_{\gamma,0}$. We treat η as a parameter whose value is constrained by nucleosynthesis, as well as large-scale structure and cosmic microwave background (CMB) radiation anisotropy measurements.

If the Universe has zero lepton asymmetry, $\eta = 0.14$. However, depending on the cosmological parameters, this may not be the value that gives the best agreement with observations. If the cosmological constant is small or zero, $\Omega_\Lambda < 0.1$, the value $\eta \approx 4$ is favored by the combination of the large-scale structure and the CMB data [15,16]. For $\Omega_\Lambda \approx 0.5$, the range $0 < \eta < 2$ is allowed [16]. For larger values of the cosmological constant, $\Omega_\Lambda > 0.7$, lepton asymmetry must be small [15–17], and $\eta \approx 0.14$.

The $\nu\bar{\nu}$ annihilation mean-free path for energies above the Z pole is much greater than the Hubble distance H^{-1}. Therefore, those neutrinos whose present energy is $E_{\mathrm{res}} \pm \delta E$ travel unabsorbed to redshifts $z_a = 2\Gamma_Z/M_Z = 0.06$, which corresponds to distance 280 Mpc$(0.65/h)$. Within this distance the mean free path is $\lambda = 1/(\sigma_{\mathrm{ann},Z} n_{\nu,\mathrm{relic}}) = 5.3\eta^{-1} \times 10^{28}$ cm, where $\sigma_{\mathrm{ann},Z} = 4\pi G_F/\sqrt{2}$. Thus, within 50 Mpc from the observer a fraction

$$P = 3.8 \times 10^{-4}\left(\frac{\eta}{0.14}\right)$$

of the ultrahigh-energy neutrinos annihilates and produces "Z bursts." The nucleons and photons from Z decays undergo a cascade of scatterings off the background photons but their energies remain largely above the GZK cutoff [5]. The resulting spectrum of these UHECR will be discussed in detail in an upcoming paper [18]. Taking into account the attenuation and absorption, each annihilation event produces $N \approx 10$ photons and protons [3] whose energies exceed the GZK cutoff. The flux of UHECR beyond the GZK cutoff is predicted to be

$$\phi_{\mathrm{CR}} = \frac{1.7}{(4\pi\ \mathrm{sr})\,(1\ \mathrm{km}^2)\,(100\ \mathrm{yr})} \times \left(\frac{N}{10}\right)\left(\frac{\eta}{0.14}\right)\left(\frac{\Omega_X}{0.2}\right)\left(\frac{h}{0.65}\right)^2 \times \left(B_\nu\,\frac{10^7 t_0}{\tau_X}\right)\left(\frac{0.07\ \mathrm{eV}}{m_\nu}\right)^{3/2}\left(\frac{10^{14}\ \mathrm{GeV}}{m_X}\right)^{5/2}. \tag{4}$$

The mass of the X particle must exceed twice the resonance energy $E_{\mathrm{res}} = M_Z^2/2m_\nu = 5.9(0.07\ \mathrm{eV}/m_\nu) \times 10^{13}$ GeV. According to Ref. [14], in the mass range $m_X \gtrsim 10^{12}$ GeV, heavy particles decaying into neutrinos are allowed by the present data as long as

$$\frac{\tau_X}{t_0} B_\nu^{-1} > 2.4 \times 10^5 \times \left(\frac{\Omega_X}{0.2}\right)\left(\frac{h}{0.65}\right)^2\left(\frac{10^{14}\ \mathrm{GeV}}{m_X}\right)^{3/4}. \tag{5}$$

As pointed out by G. Sigl [19], the limit set by the Energetic Gamma Ray Experiment Telescope on the diffuse low-energy gamma-ray flux resulting from the Z bursts could constrain this model. This question deserves further study. The other bounds usually mentioned in connection with the ultrahigh-energy neutrinos [6] do not apply because the spectrum of neutrinos in Eq. (1) is peaked near m_X. This differs drastically from the inverse power-law spectrum assumed in Ref. [6] for astrophysical sources. In our case, the number of low-energy neutrinos is negligible, and the only upper bound on the neutrino flux comes from the observations of atmospheric showers [14].

The flux of super-GZK cosmic rays in Eq. (4) is consistent with the data for some range of parameters at about $\tau_X \sim (10^5$–$10^7)t_0$, $m_X \sim (10^{13}$–$10^{15})$ GeV, $m_\nu \sim (0.01$–$1.0)$ eV. It is particularly interesting that the UHECR puzzle can be explained without fine-tuning the masses and the lifetimes of the hypothetical X particles. The mass m_X has to be at the scale where one generally expects to find some new physics. The same weakly interacting X particles could be the cold dark matter [12].

Another interesting feature of our scenario is that the neutrino mass can be in the SK range. If the neutrino density is enhanced by either gravitational clustering [3] (for neutrino masses ~eV) or due to a lepton asymmetry of the Universe [5], the parameter space for m_X, τ_X increases accordingly.

Since there is no natural reason for m_X to be exactly equal to $2E_{\rm res}$, the neutrinos produced by the X particle decays in the local cluster of galaxies give a negligible contribution to the measured flux of cosmic rays. However, those particles that decayed at redshift,

$$z_e = \frac{m_X}{2E_{\rm res}} - 1 = \frac{m_X m_\nu}{M_Z^2} - 1\,, \qquad (6)$$

have just the right energy at present for an efficient annihilation. The arrival directions of UHECR point, therefore, to their sources located in a thin spherical shell at redshift $z_e \pm \delta z$, where $\delta z = (1 + z_e)(\Gamma_Z/M_Z) = 0.03(1 + z_e)$.

If $m_X \sim 10^{14}$ GeV for $m_\nu = m_{\rm SK}$, then $z_e \sim 0.1$–1. In this case, one may hope to identify the sources with the remote clusters of galaxies at redshift z_e. In principle, this would allow one to measure m_X. The present data already show some directional clustering of events [10]. There is a 1% probability for these correlations to be accidental [10]. In the future, their statistical significance can be tested on a larger data sample. Recent studies of anisotropies in the UHECR [11] concentrated on the dark matter distribution in our Galaxy and the local group of Galaxies. In view of our results, a similar analysis of possible correlations with the known clusters of Galaxies at some fixed (but yet unknown) redshift could reveal the locations of distant sources and help determine m_X.

In any case, our scenario does not predict any correlation of the directions of UHECR with the distribution of local dark matter. If the X particle decays are many body, δz is increased because of a wider spectrum of the emitted high-energy neutrinos.

Nonthermal production of superheavy relic particles at the end of inflation [8,12] and their role in cosmology [20] have been the subject of intense studies recently. It is clear that Ω_X is a model-dependent parameter, which can be ~0.1 in many realistic models [9].

We have presented a plausible candidate source of ultrahigh-energy neutrinos that can be the explanation of the cosmic rays beyond the GZK cutoff. A weakly interacting massive particle with mass $m_X \gtrsim 10^{13}$ GeV and lifetime $\tau_X \gtrsim 10^5 t_0$ can decay into very energetic neutrinos. The expansion of the Universe redshifts the energies of the neutrinos produced in a spherical shell at $z = (m_X m_\nu/M_Z^2 - 1)$ to the value for which the cross section of $\nu\bar{\nu}$ annihilation near Earth is large. These annihilations can create a flux of photons and nucleons with energies above the GZK cutoff that is sufficient to explain the present data. The possible directional correlations of UHECR events produced in this manner reflect the matter distribution at redshift $z_e \pm \delta z$. Our scenario is consistent with the neutrino masses in the range reported by the SK experiment.

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