Axion-Like Particles as Ultra High Energy Cosmic Rays?

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If Ultra High Energy Cosmic Rays (UHECRs) with $E > 4 \times 10^{19}$ eV originate from BL Lacertae at cosmological distances as suggested by recent studies, the absence of the GZK cutoff can not be reconciled with Standard-Model particle properties. Axions would escape the GZK cutoff, but even the coherent conversion and back-conversion between photons and axions in large-scale magnetic fields is not enough to produce the required flux. However, one may construct models of other novel (pseudo)scalar neutral particles with properties that would allow for sufficient rates of particle production in the source and shower production in the atmosphere to explain the observations. As an explicit example for such particles we consider SUSY models with light sgoldstinos.

I. INTRODUCTION

Ultra High Energy Cosmic Rays (UHECRs) with energies above the Greisen-Zatsepin-Kuzmin (GZK) cutoff [1] were detected in all relevant experiments [2–6], suggesting that these particles can not originate at cosmological distances. On the other hand, there are no apparent nearby sources in their arrival direction. Therefore, something fundamental appears to be missing in our understanding of the sources, nature, or propagation of UHECRs.

The small-scale clustering of UHECR events suggests that the sources are point-like on cosmological scales [7]. Several astrophysical sources were suggested based on the coincidence of the arrival directions of some of the highest-energy events with certain astrophysical objects [8]. For example, a correlation between compact radio quasars and UHECRs was suggested in [9,11,13], although other authors found them to be insignificant [10,12]. Recently, a statistically significant correlation, at the level of chance coincidence below 10^{-5}, was found with the most powerful BL Lacertae, i.e. quasars with beams pointed in our direction [14]. The identified sources are at $z > 0.1$, far exceeding the GZK distance of $R_{\rm GZK} \approx 50$ Mpc, so that the primary UHE particles can not be protons. The photon attenuation length for energies around 10^{20} eV is of order the GZK cutoff distance, primarily due to the extragalactic radio backgrounds. While the limiting magnitude of the radio backgrounds necessary to absorb UHE photons can be determined only by numerical propagation codes [15], one can even now conclude that UHECRs with energies around 10^{20} eV are very unlikely to be photons.

The only Standard-Model particles which can reach our Galaxy without significant loss of energy are neutrinos. Two different scenarios involving UHE neutrinos have been proposed. In the first, neutrinos produce nucleons and photons via resonant Z-production with relic neutrinos clustered within about 50 Mpc from the Earth, giving rise to angular correlations with high-redshift sources [16]. However, for the interaction rates to be sufficiently high, this scenario requires enormous neutrino fluxes and an extreme clustering of relic neutrinos with masses in the eV range [17]. The second neutrino scenario invokes increased high-energy neutrino-nucleon cross sections. This could be caused by the exchange of Kaluza-Klein graviton modes in the context of extra dimensions [18] or by an exponential increase of the number of degrees of freedom in the context of string theory [19].

Another possibility to avoid the GZK cutoff is a small violation of Lorentz-invariance, a hypothesis which can not be tested in terrestrial experiments [20,21].

The GZK cutoff can be avoided also if the UHECRs consist of certain new particles. One possibility is a new stable massive hadron with a mass around 2–3 GeV [22], shifting the GZK bound to higher energies $E > 10^{21}$ eV into a range where no UHECR event has yet been found. However, it now appears that these exotic hadrons are excluded by laboratory experiments [23].

Therefore, if the UHECRs indeed originate from point sources at cosmological distances one is running dangerously short of plausible explanations for how this radiation can reach us. This perhaps desperate situation motivates us to consider other options for new particles which can traverse the universe unimpeded at high energies. Specifically, we consider the possibility of axion-like particles, i.e. electrically neutral (pseudo)scalar particles X with a relatively small mass $M_X < 10$ MeV.

Such particles must fulfill several requirements to be candidates for UHECRs. They must live long enough to reach us from a cosmological distance. They must not lose too much energy in interactions with the CMBR and other background radiations or in extragalactic magnetic fields. They must interact sufficiently strongly in or near our Galaxy or in the Earth's atmosphere to produce the observed UHE events. Finally, their interactions must allow for the production of a significant flux at the source.

We will first consider proper axions and find that they seem to be excluded as UHECRs. We then turn to more general particles and study their necessary properties to fulfill the above requirements. As an explicit example we study light sgoldstinos.

II. PROPER AXIONS

Proper axions arise from the Peccei-Quinn mechanism to solve the strong CP problem. As such their properties are governed by one main parameter, the Peccei-Quinn scale or axion decay constant f_a; astrophysical limits imply $f_a \gtrsim 10^{10}$ GeV. Axions mix with neutral pions so that their mass and interaction strength are roughly those of π^0, reduced by f_π/f_a with $f_\pi \approx 93$ MeV the pion decay constant. It is easy to see that axions live long enough and interact weakly enough with the CMBR to traverse cosmological distances unimpeded. By the same token, their interaction strength is far too weak to imagine their efficient production at the source or their efficient detection in the Earth's atmosphere.

It is less obvious, however, if they could not be produced in sufficient numbers by their coherent conversion $\gamma \to a$ in large-scale magnetic fields in the source region, and then re-appear as photons in the galaxy by the inverse process. Put another way, one might imagine the UHECRs to be photons which traverse the universe in the guise of axions.

The conversion between axions and photons in a large-scale magnetic field is essentially a particle oscillation phenomenon [24]. The diagonal elements of the mixing matrix involve m_a^2 and the square of the "photon effective mass" within the given medium, the off-diagonal element, which induces the mixing, is $2g_{a\gamma}BE$ where B is the transverse magnetic field and E the particle energy.

The oscillation length $\ell_{\rm osc}$ corresponds to the momentum difference between axions and photons of the given energy, in our case $E \approx 10^{20}$ eV. Noting that the effective photon mass is much smaller than m_a, the momentum difference is governed by the axion mass alone so that $\ell_{\rm osc} = 4\pi E/m_a^2 = 8.1~{\rm kpc}\,(E/10^{20}{\rm eV})\,({\rm meV}/m_a)^2$. On the other hand, the coherence length ℓ_B of the galactic magnetic field is probably less than 1 kpc. A significant conversion rate requires $\ell_{\rm osc} \lesssim \ell_B$, i.e. m_a larger than a few meV, not in contradiction with current limits.

The effective mixing angle between axions and photons in a magnetic field is given by $\frac{1}{2}\tan(2\theta) = g_{a\gamma}BE/m_a^2 = 0.2\,(g_{a\gamma}/10^{-10}{\rm GeV}^{-1})\,(E/10^{20}{\rm eV})\,({\rm meV}/m_a)^2$. The astrophysical limit on the axion-photon coupling is $g_{a\gamma} < 10^{-10}~{\rm GeV}^{-1}$ so that for m_a not much smaller than 1 meV the mixing angle becomes large. Put another way, for $g_{a\gamma}$ near its limit and m_a around 1 meV the transition rate in the galaxy is not ridiculously small.

The numbers are much worse for proper axions where $g_{a\gamma}$ and m_a are related by $g_{a\gamma} \approx \alpha/(2\pi f_a)$ and $m_a \approx m_\pi f_\pi/f_a$. In this case the mixing angle becomes $\theta \approx 2\times 10^{-4}(E/10^{20}{\rm eV})\,({\rm meV}/m_a) \ll 1$. Allowing the axion mass to be very small, the mixing angle could become reasonably large. On the other hand, the oscillation length then becomes very much larger than ℓ_B. The transition probability is $P(a\to\gamma) = (g_{a\gamma}B\ell_B/2)^2 \approx 3\times 10^{-8}\,(B/\mu{\rm G})^2\,(\ell_B/{\rm kpc})^2\,(10^{10}{\rm GeV}/f_a)^2 \ll 1$. A similar estimate applies to the source region where the magnetic field could be stronger, but the correlation length would be smaller. Therefore, the combined probability to produce axions at the source and to convert them into photons in the Galactic magnetic field is tiny, perhaps as small as $P \sim 10^{-16}$. Therefore, if one adjusts the proton flux from the sources to the observed flux below the GZK cutoff, then no significant axion flux will be produced above the cutoff. Therefore, proper axions do not work for this scenario.

Even if one dials $g_{a\gamma}$ and m_a independently, the numbers look discouraging as one would need a huge rate of UHE photon production in the source to compensate for small transition rates both in the source and galaxy and one would need parameter values near their exclusion limits.

III. GENERIC AXION-LIKE PARTICLES

Since proper axions are apparently not able to explain the UHECR phenomenon, we next turn to a more exotic new scalar X; a similar analysis for pseudoscalars is straightforward. The new particle is assumed to couple to gluons and photons via nonrenormalizable interactions of the form *

$$\mathcal{L} = g_g X G^a_{\mu\nu} G^{\mu\nu}_a~, \qquad \mathcal{L} = g_\gamma X F_{\mu\nu} F^{\mu\nu}~. \tag{1}$$

Only these two interactions will be important, so we assume that the coupling to other Standard-Model particles are suppressed because, say, they proceed through loops or are proportional to small Yukawa constants.

If $M_X < 2m_\pi = 270$ MeV, the dominant decay mode is into two photons:

$$\Gamma(X\to\gamma\gamma) = \frac{g_\gamma^2 M_X^3}{4\pi}~, \tag{2}$$

because the direct coupling to electrons is suppressed by assumption. If this light particle has the energy E_X it propagates through the Universe without decay if

$$R_{\rm Universe} \lesssim L_{\rm decay} = \frac{E_X}{\Gamma_X M_X}, \tag{3}$$

where Γ_X is essentially identical with the two-photon decay rate Eq. (2). Therefore, we need to require

$$g_\gamma \lesssim 1.6\times 10^{-11}~{\rm GeV}^{-1}\sqrt{\frac{E_X}{10^{20}~{\rm eV}}}\left(\frac{10~{\rm MeV}}{M_X}\right)^2 \tag{4}$$

if these particles are supposed to reach us from cosmological distances.

*The axion-photon coupling of the previous section was based on the normalization $\mathcal{L}_{a\gamma} = (g_{a\gamma}/4)aF\widetilde{F} = g_{a\gamma}a\mathbf{E}\cdot\mathbf{B}$.

Propagating through the Universe, the light scalar X may also disappear by interactions with the CMBR. For $E_X \approx 10^{20}$ eV, the CM energy is $E_{\rm cm} \approx (2E_X\omega_0)^{1/2} \approx 350$ MeV, where $\omega_0 \approx 6 \times 10^{-4}$ eV is the average energy of relic photons. Pairs of light charged particles $A^\pm$ are produced with the cross section $\sigma(X\gamma \to A^+A^-) = \alpha g_\gamma^2/16$. With a relic photon number density of about 400 cm^{-3} the requirement $R_{X\gamma\to A^+A^-} > R_{\rm Universe}$ gives $g_\gamma < 1$ GeV^{-1}. Similar estimates apply to other possible processes like $X\gamma_{\rm CMB} \to \gamma\pi^0$. Therefore, the tiny photon coupling required by Eq. (4) guarantees the absence of a GZK cutoff for the X particles.

Both the production of X particles at the source and their interaction in the atmosphere require rather large cross sections, comparable to strong ones. For X particles with the characteristic energy scale g_g^{-1} this is possible only if the CM energy in the system is close to this scale, but not significantly higher so that the effective interactions (1) are still meaningful. Typical CM energies of UHECR interactions with nucleons are $E_{\rm cm} \approx 100$–300 TeV. We can estimate the interaction cross section with nucleons at such energies as

$$\sigma_X = \sigma_s \, \frac{\alpha_X}{\alpha_s} \, . \tag{5}$$

The suppression factor

$$\frac{\alpha_X}{\alpha_s} = \frac{(E_{\rm cm} g_g)^2}{4\pi\alpha_s} \tag{6}$$

should not be very small.

We next turn to the X mean free path (mfp) ℓ_X in the Earth's atmosphere. Since our particle exhibits strong interactions we estimate ℓ_X by analogy with the proton mfp ℓ_p as $\ell_X = \ell_p\,(\alpha_s/\alpha_g)$. To initiate an atmospheric shower, X should have a relatively small mfp. Assuming $\ell_X < 10\,\ell_p$ and using Eq. (6) and $\alpha_s = 0.1$ we estimate

$$g_g > 1.1 \times 10^{-6}\ {\rm GeV}^{-1} \sqrt{\frac{10^{20}\ {\rm eV}}{E_X}} \, . \tag{7}$$

The inequalities (4) and (7) determine the g_g range suitable for explaining the UHECRs above the GZK cutoff.

How are the X-particles produced at an astrophysical source like a quasar? If our estimate for the cross section Eq. (5) is valid, UHE X particles will be efficiently produced in the high-energy tail of the proton spectra by proton-proton collisions while their production at low energies will be negligible. Therefore, we can expect that the proton flux from the source at low energies will continue with the same slope at high energies due to the X component. Only part of the initial proton energy will be transfered to the X particles; probably they will be produced on the peak of the gluon distribution function with $E \approx 0.1E_p$. However, once produced they will escape more easily from the source compared with protons precisely because their cross section is smaller.

Many bounds on axion-like particles arise from cosmology, astrophysics and laboratory measurements [25,26]. Still, there remain regions in parameter space where X particles can explain UHECRs without contradicting these limits. In Fig. 1 we present the experimentally allowed regions in the space (g_γ, M_X) where the inequality (4) is satisfied. In each concrete model one can evaluate the effective coupling constant g_γ which has to belong to the allowed regions shown in Fig. 1. Since generally the interaction with gluons leads at higher order to an effective interaction with photons, the inequality (7) may shrink the allowed regions in Fig. 1 in concrete models.

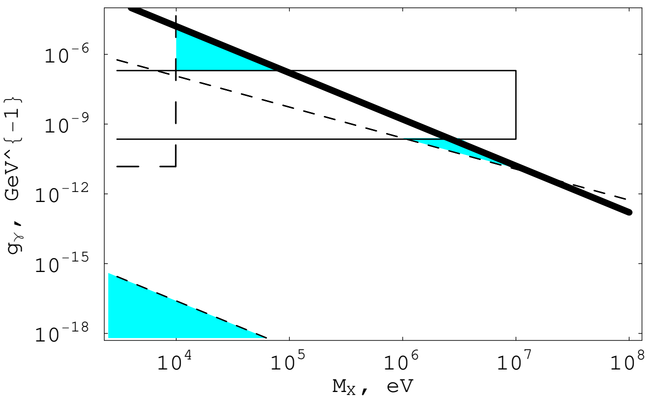

FIG. 1. The allowed region for the parameters (M_X, g_γ) are shaded in grey. The region traced by the long-dashed line is ruled out by the helium-burning life-time of horizontal-branch stars [24]. The region surrounded by a thin solid line is ruled out by SN 1987A. The region confined between short-dashed lines is ruled out by the photon background and the CMBR [26]. Below the thick solid line the inequality (4) is valid.

From the general case one can see that constraints on the X particle interactions favor a strong coupling to gluons and a tiny one to photons. Hence the first extreme example is a light scalar X which interacts at tree level only with gluons according to Eq. (1); a similar analysis applies to a light pseudoscalar. The interaction with all other SM particles arises at higher order. In particular, because the gluonic operator creates mesonic fields, the interaction $X\gamma\gamma$ emerges with a coupling constant respecting the hierarchy $g_\gamma/g_g \sim \alpha/(4\pi) \sim 10^{-3}$. In view of this relationship the inequality (7) allows only the region of parameter space which corresponds to the upper shaded region in Fig. 1. Unfortunately, this allowed region corresponds to a fairly small $g_g^{-1} \sim 0.1$–5 TeV. Therefore, our nonrenormalizable model for X-baryon scattering in the atmosphere becomes invalid because it should proceed at 100 TeV in the CM frame.

This example shows that the lowest region in Fig. 1 is unphysical, because the condition (7) requires the hierarchy $g_\gamma/g_g \sim 10^{-10}$, which is impossible due to loop contributions. The $M_X \sim$ MeV region in Fig. 1 can still exist in models with a hierarchy between photon and gluon couplings, but this requires a two order of magnitude fine-tuning for the ratio g_γ/g_g down to values of order 10^{-5}.

The other possibility is that the couplings to photons and to gluons are of the same order. In this case only the upper region in Fig. 1 is interesting because the gluon coupling should not be too small from Eq. (7). We now turn to an explicit example for a model which does not need any fine tuning of the couplings g_γ and g_g.

IV. LIGHT SGOLDSTINOS

As an example of a realistic model for X particles we consider the supersymmetric extension of the SM with a light scalar and/or pseudoscalar sgoldstino, the superpartner of the goldstino. The sgoldstino couplings are $g_g = M_3/(2\sqrt{2}F)$ and $g_\gamma = M_{\gamma\gamma}/(2\sqrt{2}F)$, where F is a parameter of supersymmetry breaking and $M_{\gamma\gamma} = M_1 \cos^2\theta_W + M_2 \sin^2\theta_W$ with M_i the corresponding gaugino masses. Therefore, the sgoldstino coupling to photons is suppressed relative to gluons only by the "hierarchy among gauginos." Therefore, this is an example for a model where X couples to photons with a similar strength as to gluons. For $M_3 = 5M_{\gamma\gamma} = 500$ GeV we obtain

$$\sqrt{F} \gtrsim 1.5 \times 10^6 \text{ GeV} \left(\frac{10^{20}\text{ eV}}{E_X}\right)^{1/4} \frac{M_X}{10\text{ MeV}} \qquad (8)$$

instead of Eq. (4) and

$$\sqrt{F} \lesssim 1.3 \times 10^4 \text{ GeV} \left(\frac{E_X}{10^{20}\text{ eV}}\right)^{1/4} \qquad (9)$$

instead of Eq. (7).

A variety of experimental limits on models with light sgoldstinos has been derived in [28]. In Fig. 2 we present the region of parameter space where sgoldstinos may act as UHECRs and are not excluded by other limits. This region corresponds to the upper region in Fig. 1.

If $E_X = 10^{21}$ eV or more, the allowed regions are larger, though no event of such energies has been observed. If $g_s = \text{const}/\Lambda$ where Λ is the scale of new physics, then at const ~ 1 we have $\Lambda = 10^2$–10^3 TeV. With $E_X = 10^{11}$ GeV we have $E_{\rm cm} = 300$ TeV for interactions with protons. Certainly Λ should exceed this value if we want to use the nonrenormalizable interactions (1). For sgoldstinos we have $M_{\rm soft} \sim \text{const}\ F/\Lambda$ and Λ should be larger than $E_{\rm cm} = 300$ TeV. Note that F is a parameter of supersymmetry breaking and Λ is something like the scale of mediation of supersymmetry breaking which generally differs from $\sqrt{F}$ but should exceed $\sqrt{F}$ if const is of order 1.

V. CONCLUSIONS

We have suggested new (pseudo)scalar particles as Ultra High Energy Cosmic Rays beyond the GZK cutoff.

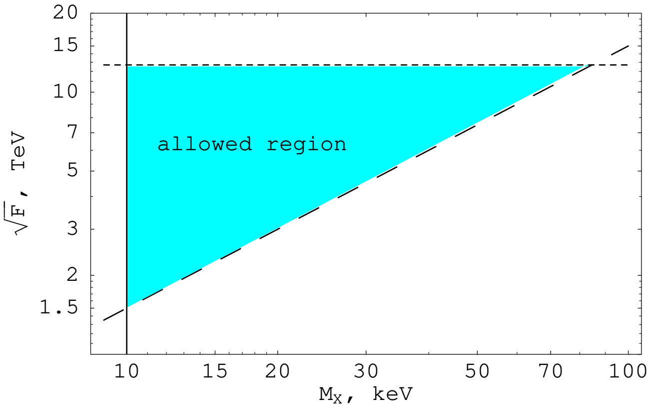

FIG. 2. Allowed region for the parameters $(M_X, \sqrt{F})$. The short-dashed line corresponds to the limit (7), the long-dashed line to (4). Sgoldstinos with masses less than 10 keV (vertical solid line) are ruled out by the helium-burning life-time of horizontal-branch stars.

Our analysis was particularly motivated by recent results suggesting that the sources of UHECRs are cosmologically point-like [7] and that at least some of the sources appear to be BL Lacertae [14] at cosmological distances.

We have calculated the required range of parameters characterizing these particles if we postulate that they should be produced in high-redshift sources, propagate through the Universe without decay or energy loss, and interact in the Earth's atmosphere strongly enough to produce extended air showers at energies beyond the GZK cutoff. The self-consistency of our analysis requires that the energy scale for new physics, which for SUSY models is the scale of mediation of supersymmetry breaking, should be close to the UHECR center-of-mass energy with nucleons of $E_{\rm cm} = 300$ TeV.

As a specific example we studied light sgoldstinos. We considered restrictions on the parameters of the model which come from laboratory experiments and observational data. We obtained the required region in parameter space of the model which obeys all existing limits.

We note that our allowed region in Fig. 2 suggests that the supersymmetry breaking scale $\sqrt{F} \sim 1$–10 TeV. Hence our light sgoldstino model can be tested in searches for rare decays of J/ψ and Υ and in reactor experiments (for details see Ref. [28]). This low scale of supersymmetry breaking may be also tested at new generation accelerators like Tevatron and LHC. Also, sgoldstino contributions to FCNC and lepton flavor violation are strong enough to probe the supersymmetry breaking scale up to $\sqrt{F} \sim 10^4$ TeV [28] if off-diagonal entries in squark (slepton) mass matrices are close to the current limits in the MSSM. Thus our light-sgoldstino scenario for UHECRs allows only small flavor violation in the scalar sector of superpartners.

Light (pseudo)scalars emerge not only in the context of supersymmetry, but also, for instance, in string theory and models with extra dimensions. Probably, such scalars also can serve as UHECRs if their effective coupling with photons obeys the limits presented in section III.

Interpreting the UHECRs as new (pseudo)scalars is, of course, extremely speculative. However, we think it is noteworthy that such an interpretation is at all possible and self-consistent without violating existing limits.

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