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Pseudo-scalar particles as ultra high energy cosmic rays?*

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*This talk is based on the results of work (Gorbunov et al. 2001).

Abstract. 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.

1 Introduction

Ultra High Energy Cosmic Rays (UHECRs) with energies above the Greisen-Zatsepin-Kuzmin (GZK) cutoff Greisen (1966); Zatsepin and Kuzmin (1966) were detected in all relevant experiments Takeda et al. (1998); Bird et al. (1995); Lawrence et al. (1991); Brownlee et al. (1968); Winn et al. (1986); Afanasiev (1996), 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 Tinyakov and Tkachev (2001a). Several astrophysical sources were suggested based on the coincidence of the arrival directions of some of the highest-energy events with certain astrophysical objects Elbert and Sommers (1995). For example, a correlation between compact radio quasars and UHECRs was suggested in Farrar and Biermann (1998, 1999); Virmani et al. (2001), although other authors found them to be insignificant Hoffman (1999); Sigl et al. (2001). 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 Tinyakov and Tkachev (2001b). 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 Kalashev et al. (1999), 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 Weiler (1982). 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 Yoshida et al. (1998); Blanco-Pillado et al. (2000). 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 Nussinov and Shrock (1999); Jain et al. (2000); Tyler et al. (2001) or by an exponential increase of the number of degrees of freedom in the context of string theory Domokos and Kovesi-Domokos (1999).

Another possibility to avoid the GZK cutoff is a small violation of Lorentz-invariance, a hypothesis which can not be tested in terrestrial experiments Coleman and Glashow (1997); Bhattacharjee and Sigl (2000).

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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 Farrar (1996); Chung et al. (1998); Albuquerque et al. (1999), 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 Clavelli (1996); Albuquerque et al. (1997); Alavi-Harati et al. (1999).

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 considered proper axions and find that they seem to be excluded as UHECRs (Gorbunov et al. 2001). In this talk we will discuss more general particles and study their necessary properties to fulfill the above requirements. As an explicit example we study light sgoldstinos.

2 Generic Axion-Like Particles

Since proper axions are apparently not able to explain the UHECR phenomenon (Gorbunov et al. 2001), we consider 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 [1]

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

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. Therefore, we need to require (Gorbunov et al. 2001):

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

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

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

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. (2) 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. From the requirement that the mean free path of the scalar particle in the atmosphere is compatible to proton's one, we can estimate g_g as following (Gorbunov et al. 2001):

$$g_g > 1.1 \times 10^{-6}\ \mathrm{GeV}^{-1} \sqrt{\frac{10^{20}\ \mathrm{eV}}{E_X}} \ . \tag{3}$$

The inequalities (2) and (3) 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 is valid citewe2001, 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 Groom et al. (2000); Masso and Toldra (1995). 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 (2) 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 (3) may shrink the allowed regions in Fig. 1 in concrete models.

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 exam-

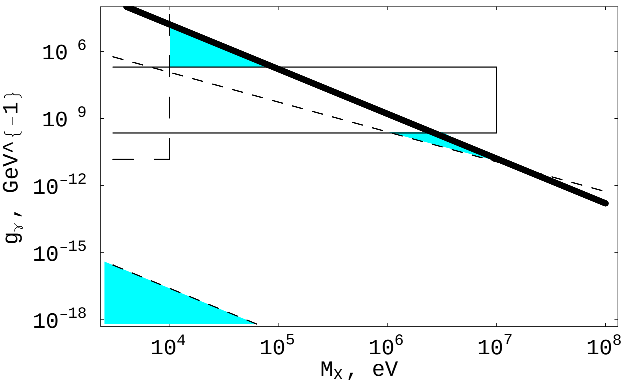

Fig. 1. The allowed region for the parameters (M_X, g_γ) are shaded in grey. The region traced by the long-dashed line is ruled out by the helium-burning life-time of horizontal-branch stars Raffelt (1996). The region surrounded by a thin solid line is ruled out by SN 1987A. The region confined between short-dashed lines is ruled out by the photon background and the CMBR Masso and Toldra (1995). Below the thick solid line the inequality (2) is valid.

ple 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 (3) 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 (3) 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. (3). 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.

3 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

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

instead of Eq. (2) and

$$\sqrt{F} < 1.3 \times 10^4 \text{ GeV} \left(\frac{E_X}{10^{20} \text{ eV}}\right)^{1/4} \tag{5}$$

instead of Eq. (3).

A variety of experimental limits on models with light sgoldstinos has been derived in Gorbunov (2000). 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.

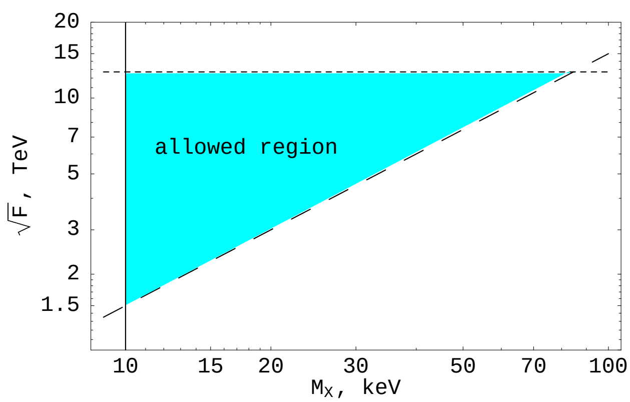

Fig. 2. Allowed region for the parameters $(M_X, \sqrt{F})$. The short-dashed line corresponds to the limit (3), the long-dashed line to (2). Sgoldstinos with masses less than 10 keV (vertical solid line) are ruled out by the helium-burning life-time of horizontal-branch stars.

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 $E_{\text{cm}} = 300$ TeV for interactions with protons. Certainly Λ should exceed this value if we want to use the nonrenormalizable interactions (1). For sgoldstinos we have $M_{\text{soft}} \sim$ const F/Λ and Λ should be larger than $E_{\text{cm}} = 300$ 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.

4 Conclusions

We have suggested new (pseudo)scalar particles as Ultra High Energy Cosmic Rays beyond the GZK cutoff. Our analysis was particularly motivated by recent results suggesting that the sources of UHECRs are cosmologically point-like Tinyakov and Tkachev (2001a) and that at least some of the sources appear to be BL Lacertae Tinyakov and Tkachev (2001b) 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. Gorbunov (2000)). 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 Gorbunov (2000) 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 2.

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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