Long-lived neutralino and ultra-high energy cosmic rays

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Abstract

Secondary photons from decays of metastable neutralinos can contribute to the ultra-high energy cosmic ray flux. Neutralino production rate is too low in acceleration mechanisms to affect the cosmic ray spectrum without emitting enormous energy in photons and neutrinos. Contrary, in top-down models with sources not concentrated in galactic halos, neutralino decays change the spectrum significantly. We estimate the parameters of a model in which photons from neutralino decays are responsible for cosmic ray events with energies above 10^{20} eV, and figure out distinctive experimental signatures for this model.

1. Current experimental data on ultra-high energy (UHE) cosmic ray (CR) spectrum are controversial. Results of AGASA experiment [1] indicate the absence of the so-called GZK feature [2], a cutoff in the spectrum at energies above a few times 10^{19} eV due to attenuation of high energy protons and photons on cosmic background radiation. Contrary, recently published spectrum obtained by HIRES experiment [3] exhibits this cutoff. Other experiments had either low statistics or insufficient precision to clearly support either absence or presence of the GZK cutoff in the spectrum.

On the other hand, *all* experiments (including HIRES) have observed cosmic rays with energies as high as $(1 \div 3) \cdot 10^{20}$ eV . Recently found [4] impressive correlations of the arrival directions of UHECRs registered by AGASA and Yakutsk experiments[1] with positions of gamma-ray loud BL Lac type objects imply that a significant fraction of the extremely energetic particles may originate at cosmological distances. Then, attenuation on the background photons excludes protons and photons as possible candidates for these particles.

One of suggested ways to solve the problem is to consider other particles which do not attenuate significantly on photonic background. Neutrino is an obvious candidate, but neutrino primaries are excluded by the atmospheric shower development [5]. However, UHE neutrinos can scatter off the relic antineutrinos (and vice versae) via the Z-resonance. The sites of these so-called Z-bursts serve as secondary sources of photons and nucleons of somewhat smaller but still very high energy. If these scatterings take place at the distance from the Earth less than the nucleon's and photon's energy attenuation length,

[1]HIRES data were not published, and we are not aware of any such analysis of them.

the Z decay products could contribute to the observed UHECR flux [6]. Required neutrino energy for the resonance is

$$E_{\rm res} \approx \frac{4\ \mathrm{eV}}{m_\nu} \cdot 10^{21}\ \mathrm{eV}. \quad (1)$$

Other proposals for non-attenuating particles include rather exotic light supersymmetric hadrons [7] and light axion-like particles [8].

In this talk, we propose an alternative to the Z-burst mechanism which shares a number of its features but does not require extraordinary high particle energies, Eq. (1). Similarly to neutrino, neutralino can travel for cosmological distances unattenuated. The lightest of superpartners of the Standard Model particles can, in some supersymmetric models, decay either to lighter gravitino and non-supersymmetric particles (if R parity is conserved), or to non-supersymmetric particles alone with R parity violated. These decays can occur more frequently in our cosmological neighbourhood, if the lifetime of the particle in the laboratory frame is of order but somewhat less than the age of the Universe. This gives rise to the super-GZK secondary particles in a way analogous to the Z burst. We note that neutralino-induced atmospheric showers would be very similar to those induced by neutrinos and hence are excluded on equal footing with the neutrino events.

The dominant decay mode of neutralino is photonic in models we consider here. This means that a signature of this mechanism is presence of photon-induced atmospheric showers. Current experimental data restricts the fraction of photonic showers to be less than $(28 \div 48)\%$ at the energies $E \lesssim 10^{19.5}$ eV [10]. However, at higher energies the bounds are much weaker, $(50 \div 67)\%$ [10]. We will see below that the most probable implementation of our mechanism is to explain the super-GZK events in the frameworks of a top-down mechanism while relating the events below 10^{20} eV to protons accelerated in active galaxies [3, 11].

2. To estimate the required neutralino lifetime and flux, we roughly approximate the decay rate of neutralinos as well as the rate of energy loss of photons with exponentials of the distances travelled by particles. We denote the width of decay (neutralino $\to$ photon $+\ldots$), measured in the laboratory frame, as Γ; and the mean energy attenuation length of a photon on the cosmic IR and radio background as $l \sim 100$ Mpc. We suppose that the sources are distributed in the Universe with the evolution index m,

$$dn(r) = n_0 4\pi r^2 \left(1 + \frac{r}{R}\right)^m dr,\ \ r < R,$$

where r is the distance from the Earth.

The total UHE photon flux on the Earth, n_γ, can be expressed via the total neutralino flux from all sources, n_χ, as

$$n_\gamma = n_\chi \frac{\Gamma}{\Gamma - 1/l} \frac{\int_0^R dr\, r^2\ \left(1+\frac{r}{R}\right)^m \left(\mathrm{e}^{-\Gamma/l} - \mathrm{e}^{-\Gamma/r}\right)}{\int_0^R dr\, r^2\ \left(1+\frac{r}{R}\right)^m}.$$

For given m and R, n_γ/n_χ has a broad maximum as a function of Γ. We present in Table 1 the neutralino lifetimes for three sets of values of distribution parameters. ¿From the last row in Table 1 one can see that the fine tuning of Γ need not be very strong. Note

m	-3	0	$+3$
R, Gpc	1	4	2
maximal n_γ/n_χ	0.070	0.013	0.025
τ at maximal n_γ/n_χ	1.0	5.6	2.9
τ at half maximal n_γ/n_χ	0.2...4.2	1.8...20.6	1.4...8.2

Table 1: R and m are parameters of the source distribution, τ is neutralino lifetime in the rest frame in units of 10^8 s $\cdot \left(\frac{50 \text{ GeV}}{M}\right)$, M is the neutralino mass.

that the presence of a particle with lifetime $\gtrsim 10^4$ s which decays to photons can affect Big Bang nucleosynthesis due to subsequent photodisintegration of light nuclei [15], unless the reheating temperature, and hence the particle abundance, are low enough.

3. Let us turn now to specific supersymmetric models with metastable neutralino. They consist of models with R parity breaking where neutralino LSP can decay to non-supersymmetric particles, and models with gravitino LSP and conserved R parity (gauge-mediated supersymmetry breaking (GMSB) [16] and certain no-scale supergravity models [17]). In what follows, we will concentrate on GMSB scenario.

The lifetime of neutralino-NLSP in the restframe is

$$\tau = \frac{16\pi^2}{\cos^2\theta_W}\frac{F^2}{M^5},$$

where θ_W is the weak mixing angle, M is the neutralino mass, and F is the scale of dynamical SUSY breaking. The latter is related to the gravitino mass, $m_{3/2}$, as

$$F = \sqrt{3}M_* m_{3/2};$$

$M_* = 2.4 \cdot 10^{18}$ GeV is the reduced Planck mass. We obtain

$$F = 2.8 \cdot 10^{19} \text{ GeV}^2 \left(\frac{\tau}{10^8 \text{s}}\right)^{1/2} \left(\frac{M}{50 \text{ GeV}}\right)^{5/2}, \tag{2}$$

$$m_{3/2} = 6.5 \text{ GeV} \left(\frac{\tau}{10^8 \text{s}}\right)^{1/2} \left(\frac{M}{50 \text{ GeV}}\right)^{5/2}. \tag{3}$$

Gravitino is a stable particle due to R parity conservation, and its mass is constrained by the condition that relic gravitinos do not overclose the Universe [18]. For $m_{3/2}$ in the GeV range and for reheating temperature low enough to satisfy nucleosynthesis constraints on τ, the overclosure constraints are satisfied.

The values (2), (3) are on the upper margins for usual gauge mediation but can be natural in models of direct gauge mediation. Indeed, let us consider probably the simplest complete model of GMSB [19]. There, supersymmetry breaking is communicated directly from the strongly interacting sector to the MSSM, and

$$M \approx \frac{5}{6\pi}\alpha_1(s)\frac{F}{s},$$

where s is the messenger scale, and $\alpha_1(s)$ is the $U(1)_Y$ coupling constant taken at the scale s. For $M \sim 50$ GeV and values of F obtained above, Eq.(2), this corresponds to $s \sim 10^{14}...10^{15}$ GeV, depending on the required neutralino lifetime. These values of s are within the region allowed for the model of Ref.[19] and low enough to suppress supergravity contributions to soft masses with respect to GMSB contributions. Note that with such high mediation scale, the squarks are not so heavy as in conventional GMSB models.

4. The mechanisms responsible for creation of UHE particles can be divided into three groups with distinctive observational signatures:

(1) acceleration in astrophysical sources – arrival directions point back to the sources, GZK cutoff is present in the spectrum assuming cosmological distribution of the sources and protons or photons as UHE particles; GZK cutoff is absent assuming non-attenuating UHE particles. This option seems to be favoured by the data at energies below 10^{20} eV;

(2) decays of metastable relic heavy particles or of short-lived heavy particles originated in turn from decays of metastable topological defects which are distributed following the Cold dark matter (CDM) density: the sources are concentrated in the halos of galaxies, and the dominant contribution to the observed UHECR flux comes from the halo of the Milky Way (above GZK energy, about 97% for nucleons and photons or $(15 \div 30)\%$ for non-attenuating UHE particles) [12]. Distribution of arrival directions exhibits large-scale anisotropy due to the non-central position of the Sun in the Milky Way [12]. GZK cutoff is absent in the spectrum;

(3) decays of short-lived heavy particles originated in turn from decays of metastable topological defects which do not follow the CDM distribution (an example of a topological defect which does not follow the CDM density but is distributed more or less homogeneously is provided by cosmic necklaces [13]): arrival directions of CRs distributed uniformly (unless there are only a few topological defects in the Universe), partial GZK cutoff [14] is present for protons or photons; it is absent for non-attenuating particles.

We now consider different mechanisms of neutralino production and check whether the mechanisms can produce the required UHECR flux and not violate other observational constraints. We will see that in acceleration mechanisms, option (1), required neutralino flux can hardly be produced.

Indeed, the most probable mechanism of production of neutralinos in astrophysical accelerators is in proton-proton collisions. For instance, this could occur in hot spots of active galaxies. All produced supersymmetric particles decay promptly to NLSP. To calculate the total neutralino production cross section, one thus has to sum over all supersymmetric species. A collection of expressions for cross sections can be found in Ref.[20], and approximations for parton distributions can be extrapolated from Ref.[21]. At the energies relevant to UHE production, the dominant SUSY production channel is gluon fusion. It is easy to check that the partial cross section $\sigma_{\rm SUSY}/\sigma_{pp} \sim 10^{-8}$ at these energies, where we extrapolated the total pp cross section from Ref.[22]. If the UHE protons do not escape from the source before collision with soft protons (this is the case, for instance, for the hot spots of active galaxies), then the total flux of UHE protons in all sources should exceed the observed UHECR flux by a factor of about 10^9:

$$n_p \approx \left(\frac{\sigma_{SUSY}}{\sigma_{pp}}\right)^{-1} \frac{n_\gamma}{n_\chi} \sim 10^9 n_\gamma .$$

The observed UHECR energy flux at energies $E \gtrsim 10^{20}$ eV is

$$E^2 J_{CR}(E) \approx 1 \text{ eV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}.$$

The protonic flux of $10^9 E^2 J_{CR}(E)$ is excluded by the following reasons. First, the protons loose their energy by GZK mechanism but do not disappear. Instead, they contribute to the CR flux at lower energies [23]. The energy flux of protons at sub-GZK energies is well measured and is only 10 times larger than the flux at 10^{20} eV. Second, the dominant part of the energy flux in pp collisions is released, roughly in equal amounts, in photons and neutrinos – decay products of multiple π mesons. The photons loose their energy in electromagnetic cascades and contribute [24] to the gamma ray background measured by EGRET [25] which allows for $J_p/J_{CR} \lesssim 10^3$ and not 10^9. The constraints connected to protons and photons can in principle be cured by very high densities in the sources, so that the protons do not leave the source at all[2]. However, neutrinos cannot be absorbed and overshoot the current experimental limits (see Ref. [26] for a recent compilation of data) by three orders of magnitude. The only possibility to avoid neutrino production is to have enormous densities in the source, $\sim 10^{19}$ protons/cm^{-3}. Then charged pions, which carry about 2/3 of the energy of the products of pp collisions, would interact before their decay and loose energy in pionic cascades so efficiently that neutrinos would be emitted only with low energies. These neutrinos would contribute to larger atmospheric neutrino flux. These densities are hardly possible in realistic astrophysical sources.

5. We conclude that in the context of the acceleration mechanism, metastable neutralions are irrelevant for UHECRs. Contrary, in the "top-down" mechanisms, supersymmetric particles (which promptly decay to neutralino in our case) can carry about 40% of the energy of the original heavy particle [9, 27]. Photons from late neutralino decays affect significantly the UHECR spectrum in the case of homogeneously distributed sources (case (3)). The partial GZK cutoff inherent in these mechanisms is washed out because neutralino decay probability is higher in our cosmological neighbourhood. Currently, only a limited number of models of the type (3) are marginally consistent with EGRET measurements [25] of gamma ray background (see Ref.[28] for examples of such models). With metastable neutralinos, EGRET constraints are easily satisfied. The distinctive features of the mechanism we discuss here seen in future experiments will be:

— neutralino which does not decay in the detector at LHC;

— absence of positional correlations of CRs with specific astronomical objects at energies $E > 10^{20}$ eV;

— global isotropy of arrival directions (including absence of galactic anisotropy) at $E > 10^{20}$ eV;

— high fraction of photons at $E > 10^{20}$ eV.

In the case (2) of CDM-like distribution of the sources, the dominant part of the UHECRs originate from decays of heavy particles within the Milky Way. Unstable neutralino can affect observable features of CRs in this case only if it decays within halo, that is its lifetime at rest is less than ~ 100 s.

[2]The similar problem appears for the Z burst mechanism if one assumes neutrino origin from pp collisions in astrophysical accelerators. In this case, $J_p/J_{CR} \sim 10^4$ is required, and the on-site absorption can help, though not in the most probable astrophysical sources [26].

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References

[1] M. Takeda *et al.*, astro-ph/0209422.

[2] K. Greisen, Phys. Rev. Lett. **16** (1966) 748; G. T. Zatsepin and V. A. Kuzmin, JETP Lett. **4** (1966) 78 [Pisma Zh. Eksp. Teor. Fiz. **4** (1966) 114].

[3] T. Abu-Zayyad *et al.* [High Resolution Fly's Eye Collaboration], astro-ph/0208301.

[4] P. G. Tinyakov and I. I. Tkachev, JETP Lett. **74**, 445 (2001) [Pisma Zh. Eksp. Teor. Fiz. **74**, 499 (2001)]; D. S. Gorbunov *et al.*, Astrophys. J. **577** (2002) L93.

[5] R. M. Baltrusaitis *et al.*, Phys. Rev. D **31** (1985) 2192; N. Inoue [AGASA Collaboration], in *Proc. of the 26th International Cosmic Ray Conference (ICRC 99)*, Salt Lake City, **1** (1999) 361.

[6] D. Fargion, B. Mele, and A. Salis, Astrophys. J. **517** (1999) 725; T. J. Weiler, Astropart. Phys. **11** (1999) 303; S. Yoshida, G. Sigl, and S. J. Lee, Phys. Rev. Lett. **81** (1998) 5505; Z. Fodor, S. D. Katz, and A. Ringwald, Phys. Rev. Lett. **88** (2002) 171101; A. Ringwald, hep-ph/0111112; Z. Fodor, S. D. Katz, and A. Ringwald, hep-ph/0203198; O. E. Kalashev *et al.*, Phys. Rev. D **65** (2002) 103003.

[7] D. J. Chung, G. R. Farrar, and E. W. Kolb, Phys. Rev. D **57** (1998) 4606; I. F. Albuquerque, G. R. Farrar, and E. W. Kolb, Phys. Rev. D **59** (1999) 015021.

[8] D. S. Gorbunov, G. G. Raffelt, and D. V. Semikoz, Phys. Rev. D **64** (2001) 096005.

[9] V. Berezinsky and M. Kachelriess, Phys. Lett. B **422** (1998) 163.

[10] M. Ave *et al.*, Phys. Rev. D **65** (2002) 063007; K. Shinozaki *et al.*, Astrophys. J. **571** (2002) L117.

[11] V. Berezinsky, A. Z. Gazizov, and S. I. Grigorieva, hep-ph/0204357; astro-ph/0210095.

[12] S. L. Dubovsky and P. G. Tinyakov, JETP Lett. **68**, 107 (1998).

[13] V. Berezinsky, P. Blasi, and A. Vilenkin, Phys. Rev. D **58** (1998) 103515.

[14] P. Bhattacharjee, C. T. Hill, and D. N. Schramm, Phys. Rev. Lett. **69** (1992) 567.

[15] T. Gherghetta, G. F. Giudice, and A. Riotto, Phys. Lett. B **446** (1999) 28; E. Holtmann *et al.*, Phys. Rev. D **60**, 023506 (1999)

[16] For reviews and references, see: G. F. Giudice and R. Rattazzi, Phys. Rept. **322** (1999) 419; S. L. Dubovsky, D. S. Gorbunov, and S. V. Troitsky, Phys. Usp. **42** (1999) 623 [Usp. Fiz. Nauk **169** (1999) 705].

[17] For review and references, see: A. B. Lahanas and D. V. Nanopoulos, Phys. Rept. **145** (1987) 1.

[18] T. Moroi, H. Murayama, and M. Yamaguchi, Phys. Lett. B **303** (1993) 289.

[19] K. Agashe, Phys. Lett. B **435** (1998) 83.

[20] T. Plehn, hep-ph/9809319.

[21] H. L. Lai *et al.*, Phys. Rev. D **51** (1995) 4763.

[22] K. Hagiwara *et al.* [Particle Data Group Collaboration], Phys. Rev. D **66** (2002) 010001.

[23] E. Waxman and J. N. Bahcall, Phys. Rev. Lett. **78** (1997) 2292; Phys. Rev. D **59** (1999) 023002; K. Mannheim, R. J. Protheroe, and J. P. Rachen, Phys. Rev. D **63** (2001) 023003; O. E. Kalashev *et al.*, hep-ph/0205050.

[24] V. S. Berezinsky, in: *"Astrophysics Of Cosmic Rays,"* Amsterdam, Netherlands: North-Holland (1990); P. S. Coppi and F. A. Aharonian, Astrophys. J. **487** (1997) L9.

[25] P. Sreekumar *et al.*, Astrophys. J. **494** (1998) 523.

[26] D. S. Gorbunov, P. G. Tinyakov, and S. V. Troitsky, Astropart. Phys. (2002), to appear (astro-ph/0206385).

[27] A. Ibarra and R. Toldra, JHEP **0206** (2002) 006; C. Barbot and M. Drees, Phys. Lett. B **533** (2002) 107; C. Barbot *et al.*, hep-ph/0207133.

[28] G. Sigl *et al.*, Phys. Rev. D **59** (1999) 043504.