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. The neutralino production rate is too low in acceleration mechanisms to affect the cosmic ray spectrum without emitting enormous energy in photons and neutrinos. However, 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. The results of the AGASA experiment [1] indicate the absence of the GZK feature [2], a cutoff in the spectrum at energies above a few times 10^{19} eV due to the attenuation of high energy protons on cosmic background radiation. However, recently published spectrum obtained by the HIRES experiment [3] exhibits this cutoff. Other experiments had either low statistics or insufficient precision to clearly support either the absence or the 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, impressive correlations have been found [4] between the arrival directions of UHECRs

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registered by the AGASA and Yakutsk experiments[1] with the positions of gamma-ray loud BL Lac type objects. This implies that a significant fraction of the extremely energetic particles may originate at cosmological distances. Attenuation on the background photons then excludes protons and photons as possible candidates for these particles.

One of the suggested ways to solve the problem is to consider other particles which do not attenuate significantly on the photonic background. The energy attenuation length of photons is of the same order as that of protons. Neutrinos are obvious candidates, but neutrino primaries are excluded by the atmospheric shower development [5]. However, UHE neutrinos can scatter off the relic antineutrinos (and vice versa) 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 a distance from the Earth less than the nucleon's and photon's energy attenuation length, the Z decay products could contribute to the observed UHECR flux [6]. The resonant energy of a neutrino with mass m_ν is

$$E_{\rm res} \approx \frac{4\ {\rm eV}}{m_\nu} \cdot 10^{21}\ {\rm eV}. \tag{1}$$

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 the extraordinarily high particle energies obtained from Eq. (1). Like the neutrino, the neutralino can travel for cosmological distances unattenuated [9]. The lightest 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 neighbourghood 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 mechanism. We note that neutralino-induced atmospheric showers would be very similar to those induced by neutrinos and hence can be excluded on an equal footing to the neutrino events.

The dominant decay mode of the neutralino is photonic in the models we consider here. This means that a signature of this mechanism is the presence of photon-induced atmospheric showers. Current experimental data restrict

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[1] The HIRES stereo data has not been published, nor are we aware of any analysis of the data.

m	-2	0	$+2$
R, Gpc	1	4	2
maximal n_γ/n_χ	0.086	0.094	0.068
τ at maximal n_γ/n_χ	0.5	6.8	2.9

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 $\cdot \left(\frac{50\ \mathrm{GeV}}{M}\right)$, M is the neutralino mass.

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 framework 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 to the 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 in the comoving frame,

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

where r is the distance from the Earth, $z(r)$ is the corresponding redshift.

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

$$n_\gamma = n_\chi \frac{\Gamma}{\Gamma - 1/l} \frac{\int_0^R dr\, r^2 \left(1 + \frac{r}{R_0}\right)^{-2m-6} \left(\mathrm{e}^{-r/l} - \mathrm{e}^{-\Gamma r}\right)}{\int_0^R dr\, r^2 \left(1 + \frac{r}{R_0}\right)^{-2m-6}},$$

where $R_0 \approx 4$ Gpc is the radius of the Universe, and we calculated the fluxes in the laboratory frame. For given m and R, n_γ/n_χ has a broad maximum as a function of Γ, so the fine tuning of Γ need not be very strong. We present in Table 1 the neutralino lifetimes for three sets of values of distribution parameters. Note 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 [12] 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 with conserved R parity (these include gauge-mediated supersymmetry breaking (GMSB) [13] and certain no-scale supergravity models [14]). 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 supersymmetry 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

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

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

The gravitino is stable due to R parity conservation and its mass is constrained by the condition that relic gravitinos do not overclose the Universe [15]. 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 as well.

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 [16]. 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 the values of F obtained above using 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.[16] and low enough to suppress supergravity contributions to soft masses with respect to GMSB contributions.

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) the decay of metastable relic heavy particles or of short-lived heavy particles originating in turn from the decay 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 partcles) [17]. Distribution of arrival directions exhibits large-scale anisotropy due to the non-central position of the Sun in the Milky Way [17]. GZK cutoff is absent in the spectrum;

(3) the decay of short-lived heavy particles originated in turn from the decay 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 [18]): arrival directions of CRs are distributed uniformly (unless there are only a few topological defects in the Universe), partial GZK cutoff [19] 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 the 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. We have checked 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, in 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:

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

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 for the following reasons. Firstly, the protons lose 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. Secondly, the dominant part of the energy flux in pp collisions is released roughly in equal amounts into photons and neutrinos – decay products of multiple π mesons. The photons lose 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 evaded 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 lose energy in pionic cascades so efficiently that neutrinos would be emitted only with low energies. These neutrinos would contribute to a 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 neutralinos are irrelevant for UHECRs. On the other hand, 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 neighbourghood. Currently, only a limited number of models of the type

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[2] A 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 absorbtion can help, though [26] not in the most probable astrophysical sources.

(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 mechanism discussed here has the following distinctive signatures in future experiments:

— a neutralino which does not decay in the detector at future colliders but does not constitute the CDM;

— the 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 anysotropy) 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 neutralinos can affect observable features of CRs in this case only if they decay within the halo, that is their lifetime at rest is less than ~ 100 s.

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