Ultra-high energy LSP

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We argue that the lightest supersymmetric particles (LSP) can be produced with extremely high energies $E \gtrsim 10^{10}$ GeV in the Universe at the present epoch. Their most probable sources are decaying superheavy particles produced by topological defects or as relic Big Bang particle. We discuss the mechanisms of production of LSP at ultra-high energies (UHE) and the interaction of the UHE LSP with matter. The most attention is given to the neutralino as LSP, although the gluino is also considered as a phenomenological possibility.

Key words: Supersymmetry, cosmic rays, topological defects.

1 Introduction

Cold Dark Matter (CDM) is probably the most abundant form of matter in the Universe. A natural CDM candidate is the lightest supersymmetric particle (LSP) which is stable, if R-parity is conserved. In this *Letter*, we address the question if the LSP can be also among the ultra-high energy (UHE) particles filling the Universe. Theoretically the best motivated candidates for LSP are the neutralino and gravitino. We shall not consider the latter, because it is practically undetectable as UHE particle. Therefore, we pay most attention to the neutralino.

In all elaborated SUSY models the gluino is not the LSP. Only, if the dimension-three SUSY breaking terms are set to zero by hand, gluino with mass $m_{\tilde{g}} = \mathcal{O}(1\text{ GeV})$ can be the LSP [1]. There is some controversy if the low-mass window 1 GeV $\lesssim m_{\tilde{g}} \lesssim$ 4 GeV for the gluino is still allowed [2,3]. Nevertheless, we shall study the production of high-energy gluinos and their interaction with matter being inspired by the recent suggestion [4] (see also [5]), that the atmospheric showers observed at the highest energies can be produced by colourless hadrons containing gluinos. We shall refer to any of such hadron as $\tilde{g}$-hadron ($\tilde{G}$). Light gluinos as UHE particles with energy $E \gtrsim 10^{16}$ eV were considered in some detail in the literature in connection with Cyg X-3 [6,7]. Additionally, we consider heavy gluinos with $m_{\tilde{g}} \gtrsim 150$ GeV [5].

Three mechanisms for the production of UHE LSP can be identified.
(i) They can be produced in "astrophysical accelerators" due to the interaction of accelerated protons with ambient gas. This mechanism effectively works only in the case of a light gluino, and it was exploited in 80s during the Cyg X-3 epic where the *glueballino* ($\tilde{g}g$ bound state) was one of the main characters [6,7]. For UHE $\tilde{g}$-hadrons this production mechanism was indicated in Ref. [4]. The main difficulty of this mechanism is the low LSP flux, which is caused by the small cross-section for gluino production if $m_{\tilde{g}} > 1$ GeV and by the low density of the target nucleons or photons around the "accelerator".
(ii) Evaporating black holes are another possibility. High energy particles can be produced during the final stages of evaporation; the resulting spectra of cosmic rays have been discussed in Refs. [8]. However, when these spectra are combined with various observational bounds on the mass fraction of the universe in black holes (see [9] for a review), one finds that the UHE CR flux from black holes is well below the observed flux.
(iii) Decays of the supermassive particles produced either by topological defects or by Big Bang as relic particles, can naturally provide the large fluxes of UHE LSP.

The plan of this paper is as follows: We first discuss the possible sources of UHE LSP. Then we examine the cascade-production of LSP and their resulting spectrum. After that, we calculate the LSP fluxes for the two most promising sources. Finally, we examine the interactions of the UHE LSP with matter and discuss the status of (quasi-)stable gluino.

2 Topological defects and supermassive relic particles

Topological defects and supermassive relic particles are the two most promising sources. Topological defects [10] such as superconducting strings, monopoles, and monopoles connected by strings can produce UHE particles [11]. Here we will concentrate on *cosmic necklaces*, since this model seems to provide the largest UHE particle flux for fixed density of electromagnetic cascade radiation.

Cosmic necklaces are hybrid defects consisting of monopoles connected by a string. These defects are produced by the symmetry breaking $G \to H \times U(1) \to H \times Z_2$. In the first phase transition at scale η_m, monopoles are produced. At the second phase transition, at scale $\eta_s < \eta_m$, each monopole gets attached to two strings. The basic parameter for the evolution of necklaces is the ratio of monopole mass and the mass of the string between two monopoles, μd, where $\mu \sim \eta_s^2$ is the mass density of the string and d the distance between two monopoles. Strings loose their energy and can contract due to gravitational radiation. As a result, all monopoles annihilate in the end producing superheavy Higgs, gauge bosons and their supersymmetric partners which we call collectively X-particles. The rate of X-particle production can be estimated as

$$\frac{\mathrm{d}n_X}{\mathrm{d}t} \sim \frac{r^2\mu}{t^3 m_X}\,. \tag{1}$$

Similar to the case of UHE protons, the flux of UHE LSP is determined mainly by two parameters, $r^2\mu$ and m_X, which values must be of order 10^{27} GeV^2 and 10^{14} GeV, respectively, to have the flux close to the observed one. For a more complete discussion see Ref. [12]. The diffuse flux of LSP produced by the decay of X-particles from necklaces is given by

$$I_{\mathrm{LSP}}(E) = \frac{1}{4\pi}\, R(E)\, \frac{\mathrm{d}n_X}{\mathrm{d}t} \frac{\mathrm{d}N_{\mathrm{LSP}}(E)}{\mathrm{d}E}\,, \tag{2}$$

where $\mathrm{d}N_{LSP}/\,\mathrm{d}E$ is the spectrum of LSP from the decay of X-particles. Furthermore, $R(E)$ is the attenuation length $\lambda(E)$ of the LSP if $\lambda(E) < ct_0$ and $R(E) = ct_0$ otherwise, where t_0 is the age of the Universe.

If the neutralino χ is the LSP, $\lambda(E)$ is much larger than ct_0. It is determined as $\lambda(E) = (1/E \cdot \mathrm{d}E_{\mathrm{loss}}/\,\mathrm{d}t)^{-1}$ and the dominant contribution is given by the scattering of neutralino off background neutrinos, $\chi + \nu_{\mathrm{BB}} \to \chi + \nu$. The largest cross-section, $\sigma \sim G_F^2 (E/m_\chi)^2 \epsilon_\nu^2$, where ϵ_ν is the energy of the relic neutrino, is provided by the Higgsino component of the neutralino with Z^0-exchange in the t-channel. Apart from the smallness of the cross-section, λ is further reduced by the small energy transfer in one collision. The Universe becomes transparent for UHE neutralino at red shift $z < 1 \cdot 10^4$, however production of neutralinos at early cosmological epochs is not important in the case of topological defects.

The dominant energy-loss process of the $\tilde{g}$-hadron is pion production in collisions with microwave photons. Pion production effectively starts at the same Lorentz-factor as in the case of the proton. This implies that the energy of the GZK cutoff is a factor $m_{\tilde{g}}/m_p$ higher than in case of the proton. The attenuation length also increases because the fraction of energy lost near the threshold of production is small, $\mu/m_{\tilde{g}}$, where μ is a pion mass. Therefore, even for light $\tilde{g}$-hadrons, $m_{\tilde{g}} \gtrsim 2$ GeV, the steepening of the spectrum is less pronounced than for protons.

Let us now come to superheavy relic particles as a source of UHE LSP. This case is formally identical to the production of X-particles by topological defects if one replaces the RHS of Eq. (1) by n_X/τ_X. Following Ref. [13] we will use the ratio $r_X = \xi_X t_0/\tau_X$, $\xi_X = \rho_X/\rho_{\rm CDM}$ as parameter characterizing the model (here ρ_X and $\rho_{\rm CDM}$ are the mass density of X-particles and of the total CDM, respectively). The flux can be calculated by Eq. (2), where now $R(E)$ is the size of galactic halo R_h. We adopt the following astrophysical parameters for this case [13]: $R_h = 100$ kpc, $\Omega_{\rm CDM} = 0.2h^2$ and $h = 0.6$. We assume for the halo density $m_X n_X^h = \xi_X \rho_{\rm CDM}^h$ and for the extragalactic density $m_X n_X^{\rm ex} = \xi_X \Omega_{\rm CDM}\rho_{\rm cr}$, where ξ_X describes the fraction of X-particles in CDM and $\Omega_{\rm CDM}$ is the CDM density in units of the critical density $\rho_{\rm cr}$.

3 Cascade-production of LSPs at the decay of X-particle

The decay of X-particle results in a particle cascade similar to the QCD cascade in e^+e^- annihilation. The basis of the cascade development in both cases is given by probability p of production of an extra parton, $p \sim g^2 \ln Q^2 > 1$, where g is a coupling constant. In the process of the cascade development, the energy and the virtuality Q^2 of the cascade particles diminish progressively. Until the virtuality Q^2 remains larger than the SUSY scale $M_{\rm SUSY}^2 \sim (1\ \text{TeV})^2$, the decay channels to the usual particles and their supersymmetric partners have equal probabilities and the number of SUSY particles at each generation is exactly equal to that of usual particles. When Q^2 reaches $M_{\rm SUSY}^2$, the supersymmetric particles go out of equilibrium and decay to the LSP.

We performed a simplified Monte-Carlo simulation [1] of the cascade including as elementary processes the transition probabilities between fermions, sfermions, gluons, gluinos, W-bosons and winos, photons and neutralinos with probabilities similar to that in QCD. For simplicity, we assumed a common mass $M_{\rm SUSY} = 1$ TeV for all SUSY particles except the LSP. We followed the evolution until a particle reaches the virtuality $Q^2 \leq M_{\rm SUSY}^2$. In the case of the neutralino as LSP, each SUSY particle is then turned into neutralino after one or several decays. The case of heavy gluino, $m_{\tilde g} \gtrsim 100$ GeV is very similar, with the obvious difference that gluino is turned into $\tilde g$-hadron at the confinement radius.

The case of a very light gluino is different. After SUSY particles go out of equilibrium, gluinos still participate in the QCD cascade due to $g \to \tilde g + \tilde g$. The processes of gluino production and radiation of gluons by gluinos are very similar to that of quarks and one can expect that in the low-energy part of the cascade the number of gluinos is roughly equal to the number of quarks. However, in the problem considered here, we are not interested in particles with too small x and our simulation does not include this low-energy regime.

[1] A more complete Monte-Carlo simulation of the cascade is in preparation [14].

The obtained spectrum of the LSP can be well approximated for the energies at interest $E \gg M_{\rm SUSY}$ by

$$\frac{{\rm d}N}{{\rm d}E} \sim k\,\frac{1}{M_X}\left(\frac{E}{M_X}\right)^{-1.4} \tag{3}$$

with $k \sim 0.25$ for both neutralino and gluino as LSP. The fraction of energy transferred to the LSP is $f_{\rm SUSY} \sim 0.4$. In Fig. 1 and 2 we show the resulting LSP fluxes from decaying X-particles and cosmic necklaces, respectively. Moreover, the neutrino fluxes calculated in MLLA approximation and experimental data [16] are shown.

4 Interaction of UHE neutralino with matter

Let us consider the interactions of the neutralino χ relevant for their detection. They are somewhat similar to the calculations [15] for a photino. Mainly two processes are important for its interaction with matter, namely the neutralino-nucleon scattering $\chi + N \to$ all and resonant production of selectron off electrons $\chi + e \to \tilde{e} \to$ all. The first process is based on the resonant subprocess $\chi + q \to \tilde{q} \to$ all and on neutralino-gluon scattering. The latter subprocess is important, because for high energies, and consequently for small scaling variable x, the gluon content of the nucleon increases fast.

The resonant cross-section of the parton process $\tilde{\chi} + q \to \tilde{q}_{L,R} \to$ all is given by the Breit-Wigner formula as

$$\sigma^{\rm res}(\hat{s}) = \frac{\pi\,\hat{s}}{\hat{p}^2_{\rm cm}}\,\frac{\Gamma^2(\tilde{q}_{L,R} \to q + \tilde{\chi})}{(\hat{s} - M^2_{L,R})^2 + M^2_{L,R}\Gamma^2_{\rm tot}}\,, \tag{4}$$

where $s = 2E_\chi m_N$, E_χ denotes the energy of the incident neutralino, m_N the nucleon mass, $M_{L,R}$ are the masses of left- and right-chiral squarks and $\hat{s} = sx$. The total decay width $\Gamma_{\rm tot}$ of the squark depends strongly on the mass spectrum of the model. In the following, we parameterize our ignorance by $\Gamma_{\rm tot} = z\Gamma(\tilde{q}_{L,R} \to q + \chi)$ with $z \geq 1$. To obtain the neutralino-nucleon cross-section, the parton cross-section $\sigma^{\rm res}(\hat{s})$ has to be integrated with quark distribution functions $q_i(x, \hat{s})$ over x, down to $x_{\rm min} = M^2_{L,R}/s$, and summed over all quarks. The total χ-nucleon cross-section due to the neutralino gluon scattering can be similarly obtained integrating the parton cross-section with the gluon structure function of the nucleon.

The soft breaking terms of the MSSM are characterized by the following basic parameters [17]: the masses of i scalar fields, m^i_0, at the GUT scale, the masses of j gaugino fields, $m^j_{1/2}$, also at GUT scale, the ratio of the two vev's of the Higgs fields $\tan\beta = v_2/v_1$, and the Higgs mixing parameter μ. To proceed, we choose two different scenarios. In the first one, we assume universality of scalar masses m_0 and fermion masses $m_{1/2}$ at the GUT scale. In this case the neutralino is gaugino dominated in most part of the parameter space of the MSSM. To obtain a lower bound for the cross-sections we use the configuration with the largest values of parameters compatible with a no-fine tuning condition [17] ($m_0 = 308$ GeV, $m_{1/2} = 390$ GeV, and $\mu = 561$). We fix $\tan\beta = 8$ throughout. This corresponds to a neutralino with mass $M_\chi = 160$ GeV and a gaugino part of $P = Z_{11}^2 + Z_{12}^2 = 0.99$. The masses of the squarks are $M_{L,R} \approx 1000$ GeV, except the lightest stop which has $M \approx 780$ GeV.

In the second scenario, we break universality for the two Higgs doublets, keeping the universal value m_0 for all other scalars and $m_{1/2}$ for gauginos. As a result mixed and Higgsino dominated configurations appear [17]. We choose the configuration with minimal gaugino part, which is obtained for $m_0 = 1204$ GeV, $m_{1/2} = 295$ GeV, $\mu = 108$. The masses of the squarks of the first two generations are $M_{L,R} \approx 1400$ GeV, while masses of the third generation range from $1400 - 730$ GeV.

The resulting cross-sections are shown in Fig. 3 for the case of universality (gaugino dominated neutralino), and in Fig. 4 for a non-universal case and a higgsino-dominated neutralino. In each figure, the cross-section of gluon-neutralino scattering (solid line) and the cross-sections of resonant quark-neutralino scattering (dashed lines) for $\Gamma_{\rm tot} = z\Gamma(\tilde{q}_{L,R} \to q + \tilde{\chi})$ with $z = 1$ (top) and $z = 10$ (bottom) are shown. The cross-sections of all subprocesses start to grow at energies $s \gg 10^6\,(\mathrm{GeV})^2 \approx M_{L,R}^2$. The rise with s is caused by the decrease of $x_{\min} = M_{L,R}^2/s$ and $x_{\min} = (M_{L,R} + m_q)^2/s$, and the corresponding decrease of the number of partons with sufficient momentum in the nucleon. If squarks do not decay mainly into neutralino, *i.e.* $\Gamma_{\rm tot} \gg \Gamma(\tilde{q}_{L,R} \to q + \tilde{\chi})$, neutralino-gluon scattering gives in both cases the dominant contribution to the total cross-section. At energies $s \approx 10^{10}\,(\mathrm{GeV})^2$ or $E_\chi \approx 5 \cdot 10^{18}$eV, the neutralino-nucleon cross-section is about $10^{-35} - 10^{-34}$ cm^2, *i.e.* slightly lower than the neutrino-nucleon cross-section.

Let us consider now $\chi + e \to \tilde{e} \to$ hadrons which is similar to the Glashow resonant scattering $\bar{\nu}_e + e \to W \to \mu + \bar{\nu}_\mu$. The resonant energy of the neutralino is

$$E_\chi = M_{\tilde{e}}^2/(2m_e) = 9.8 \cdot 10^8 (M_{\tilde{e}}/10^3\ \mathrm{GeV})^2\ \mathrm{GeV} \tag{5}$$

and the cross-section is also given by Eq. (4). Now, $\Gamma_{\rm tot}$ is the total decay width of $\tilde{e}$ determined by the decay channels to electron and neutralino and neutrino and chargino and M is the selectron mass. For the frequency of events produced by the neutralino flux $I_\chi(E)$ in a detector with N_e target electrons one easily obtains

$$\nu = \Omega N_e E_0 I_\chi(E_0)\sigma_{\rm eff}, \tag{6}$$

where Ω is the solid angle and

$$\sigma_{\rm eff} = 2\pi\alpha_{\rm ew}\kappa^2/M_{\tilde{e}}^2 \sim 2\cdot 10^{-35}\ {\rm cm}^2 \tag{7}$$

is the effective cross-section. The factor κ depends on the composition of the neutralino and is assumed to be of order one. The resonant events with frequency (6) are produced as a narrow peak at E_χ and give an unique signature for neutralino.

5 Interactions of $\tilde{g}$-hadrons and its status as LSP

The interaction of UHE $\tilde{g}$-hadrons ($\tilde{G}$) was already considered in some detail in Ref. [7] for the case of glueballino. Two values determine the interaction of a UHE $\tilde{g}$-hadron with a nucleon. The first one is the radius of the $\tilde{g}$-hadron. This radius is inversely proportional to the reduced mass of the system and estimates of Ref. [7] give for the total $\tilde{G}$N-cross-section $\sigma \sim 1$ mb. In Ref. [5], it is argued that this cross-section is of order $\Lambda_{QCD}^{-2} \sim 10$ mb. However, for production of EAS in the atmosphere only interactions with large energy transfer are effective. For a gluino with mass $m_{\tilde{g}} \sim 3$ GeV or $m_{\tilde{g}} \gtrsim 150$ GeV the large energy transfer corresponds to scattering with large Q^2 and thus to small cross-section.

Now we consider the diffractive interaction of UHE $\tilde{g}$-hadron with nucleons. Then $\tilde{g}$-hadrons exchange with nucleons the 4-momentum Q in the t-channel fragmentating into jets of hadrons (including $\tilde{g}$-hadron). For a given energy transfer $y=(E-E')/E$,

$$Q_{\rm min}^2 = M^2 y\left((1-y)^{-1} - m_{\tilde{G}}^2/M^2\right), \tag{8}$$

where $M > m_{\tilde{G}}$ is the invariant mass of the fragmentation jet. Unless y is very small, $Q_{\rm min}^2$ is large and the corresponding cross-section $\sigma(y) \sim 1/Q_{\rm min}^2(y)$ is small. We conclude thus that a heavy $\tilde{g}$-hadron ($m_{\tilde{G}} \sim 3$ GeV or $m_{\tilde{G}} \gtrsim 150$ GeV) behaves in the atmosphere like a penetrating particle, while a very light $\tilde{g}$-hadron interacts like a nucleon.

Let us discuss now the status of the gluino as LSP. Accelerator experiments give the lower limit on the gluino mass as $m_{\tilde{g}} \gtrsim 150$ GeV [2]. The upper limit of the gluino mass is given by cosmological and astrophysical constraints, as was recently discussed in [5]. In this work it was shown that if the gluino provides the dark matter observed in our galaxy, the signal from gluino annihilation and the abundance of anomalous heavy nuclei is too high. Since we are not interested in the case when gluino is DM particle, we can use these arguments to obtain an upper limit for the gluino mass. Calculating the relic density of gluinos (similar as in [5]) and using the condition $\Omega_{\tilde{g}} \ll \Omega_{\rm CDM}$, we obtained $m_{\tilde{g}} \ll 9$ TeV.

Now we come to a very strong argument against the existence of a light stable or quasistable gluino [18]. It is plausible that the glueballino $(\tilde{g}g)$ is the lightest hadronic state of gluino [6,7]. However, *gluebarino*, i.e. the bound state of gluino and three quarks, is almost stable because baryon number is extremely weakly violated. In Ref. [18] it is argued that the lightest gluebarino is the neutral state $(\tilde{g}uud)$. These charged gluebarinos are produced by cosmic rays in the earth atmosphere [18], and light gluino as LSP is excluded by the search for heavy hydrogen or by proton decay experiments (in case of quasistable gluino). In the case that the lightest gluebarino is neutral, see [1], the arguments of [18] still work if a neutral gluebarino forms a bound state with the nuclei. Thus, a light gluino is disfavored.

The situation is different if the gluino is heavy, $m_{\tilde{g}} \gtrsim 150\ GeV$. This gluino can be unstable due to weak R-parity violation [20] and have a lifetime $\tau_{\tilde{g}} \gtrsim 1$ yr, *i.e.* long enough to be UHE carrier from remote parts of the Universe. Then the calculated relic density at the time of decay is not in conflict with the cascade nucleosynthesis and all cosmologically produced $\tilde{g}$-hadrons decayed up to the present time. Moreover, the production of these gluinos by cosmic rays in the atmosphere is ineffective because of their large mass.

6 Discussion and Conclusions

We estimated the fluxes of UHE LSP produced by the decays of supermassive X-particles ($m_X > 10^{13}$ GeV). These particles can be Big Bang relics or can be produced by topological defects. We performed a simple Monte-Carlo simulation for the development of such a cascade. The fluxes of UHE LSP are numerically evaluated for two cases: cosmic necklaces as example of topological defects, and supermassive Big Bang relic particles.

Most attention is given to neutralino, χ, as LSP. We calculated the χN-cross-sections at very high energies for two versions of "standard" MSSM with soft breaking terms: with universal scalar mass term and non-universal one. The typical values of cross-sections at extremely high energies are $\sigma \sim 10^{-34}$ cm^2 and thus the detection of UHE neutralinos is a difficult task, which needs a special discussion. If the masses of the squarks are near their experimental bound [2], $M_{L,R} \sim 180$ GeV, the cross-section can be 60 times higher.

What is important to realize is that neutralinos, which are probably the most abundant form of matter in the Universe, can naturally exist in the form of high-energy particles. The signature of UHE neutralino is a narrow resonance peak at energy $E \sim 10^9$ GeV$(M_e/1 \text{ TeV})^2$ (see Eq.(13)).

As another example of LSP we considered the gluino. This is a hypothetical case, because in all elaborated SUSY models the gluino is not the LSP. Apart from a controversial mass window, $1-4$ GeV, the gluino mass is limited from below by accelerator experiments as $m_{\tilde{g}} \gtrsim 150$ GeV, while from above it is limited cosmologically ($m_{\tilde{g}} \ll 10$ TeV). The light gluino as LSP is further disfavored due to the upper limit on concentration of heavy hydrogen or by searches for proton decay [18]. The heavy unstable gluino with mass $m_{\tilde{g}}$ in the interval $150 - 1000$ GeV and the lifetime $\tau_{\tilde{g}} \gtrsim 1$ yr is free from the above constraints and can be the carrier of UHE signal from remote parts of the Universe. Heavy $\tilde{g}$-hadrons behave in the earth atmosphere like penetrating particles: they have large cross-section, $\sigma \sim 1$ mb, for very small energy transfers but very small cross-sections for large fractions of energy transfer $y \geq 0.1$. The light $\tilde{g}$-hadrons interact like the usual nucleons.

The energy spectrum of light $\tilde{g}$-hadrons has the usual GZK-cutoff, while for heavy ones the energy of the GZK-cutoff is shifted to larger energies as shown in Fig. 2. In conclusion, we think that gluino is disfavored both as LSP and the carrier of UHE signal.

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Note added: At the moment of the submission of this paper, a paper by J. Adams *et al.* (hep-ex/9709028) has appeared which excludes a light glueballino in the mass and life time ranges of $1.2-4.6$ GeV and $2 \cdot 10^{-10} - 7 \cdot 10^{-4}$ s. While these data are not consistent with the model of Farrar *et al.* [1,4], they do not exclude a long-lived gluino with $\tau \gtrsim 1$ yr which we critically discussed.

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