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A mystery of Uhecron - any connection to UHECR?

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Abstract. The interaction properties of hadronic bound states of a light supersymmetric particle, gluino, are studied in the framework of the QGSJET Monte Carlo model. All important contributions to the interaction mechanism are taken into account. In particular, it is found that direct hard interaction of the valence gluino plays an important role in the process. The formalism is applied to the investigation of the properties of extensive air showers, initiated by such particles. Comparing the results with existing cosmic ray data, we were able to set the new limit on the gluino mass, $m_{\tilde{g}} < 5$ GeV, for gluino-hadrons to be the carriers of ultra high energy cosmic ray signal.

1 Introduction

The existence of Ultra High Energy Cosmic Rays (UHE CR) with the energies above the so-called Greisen-Zatsepin-Kuzmin cutoff (Greisen, 1966; Zatsepin and Kuzmin, 1966) is now well established experimentally (for a recent review see Nagano and Watson, 2000). There exist a wide-spread opinion that such very energetic particles have an extragalactic origin. On the other hand, usual cosmic ray primaries, protons and nuclei, emitted from distant sources have little chances to reach the earth with energies above the GZK-cutoff because of their energy losses in the interactions with the cosmic microwave background radiation. As a possible alternative one may consider stable hadronic bound states of the gluino $\tilde{g}$ in supersymmetric models in which the gluino is the lightest supersymmetric particle (Farrar, 1996; Raby, 1998). Such exotic hadrons, referred below as gluino-hadrons, could successfully mimic usual proton-induced Extensive Air Showers (EAS) and would allow to postpone the GZK-cutoff to higher energies.

The bound state of the gluino and the gluon, the so-called glueballino $\tilde{G} = \tilde{g}g$, has been discussed as a possible UHE primary already in the 80's in connection with Cyg-X3 (Berezinsky and Ioffe, 1986). More recently, the S^0, a $uds\tilde{g}$ boundstate, has been proposed as the carrier of the UHE CR signal (Farrar, 1996). A detailed investigation of S^0-induced EAS has been performed by Albuquerque *et al.* (1999), using a modified version of the SIBYLL model (Fletcher *et al.*, 1994). The authors of that work came to the conclusion that gluino masses as large as 50 GeV are consistent with current cosmic ray data. However, their analysis was not self-consistent as they neglected the contribution of minijet production in the model while assuming large cross sections for S^0-nucleus interactions. This appears to be in contradiction with the philosophy of the SIBYLL model, where the "soft" nonperturbative physics is considered to be of scaling type and very high energy hadronic interactions are dominated by hard parton processes (Fletcher *et al.*, 1994).

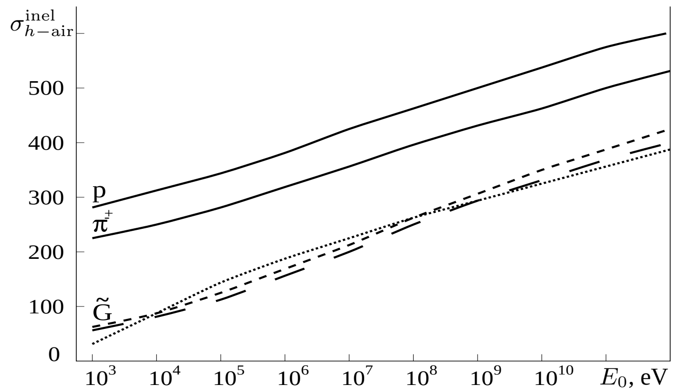

Fig. 1. Inelastic hadron-air cross section/mbarn as a function of the interaction energy for proton - p, pion - $\pi^{\pm}$, and glueballino - $\tilde{G}$; the different choices for the gluino mass are shown as dashed, long-dashed, and dotted curves for $m_{\tilde{g}} = 2$, 5, 50 GeV correspondingly.

In our recent work (Berezinsky *et al.*, 2001), the interactions of gluino-hadrons have been studied in the framework of the QGSJET Monte Carlo model (Kalmykov and Ostapchenko, 1993; Kalmykov *et al.*, 1994, 1997), known to describe successfully a great variety of existing cosmic

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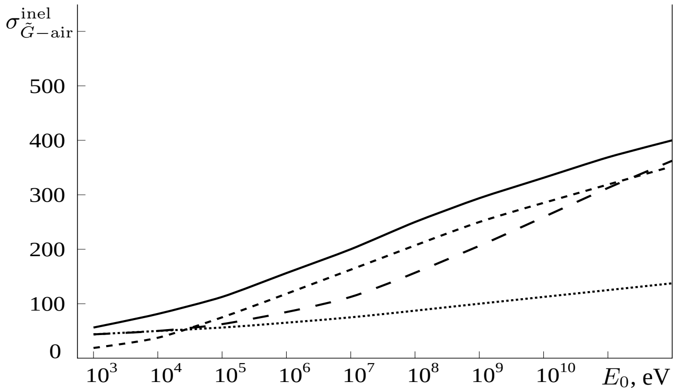

Fig. 2. Inelastic $\tilde{G}$-air cross section/mbarn for $m_{\tilde{g}} = 5$ GeV; the curves correspond to different assumptions concerning the interaction mechanism ("total" – smooth, "direct hard" – dashed, "semihard" – long-dashed, "soft" – dotted), as explained in the text.

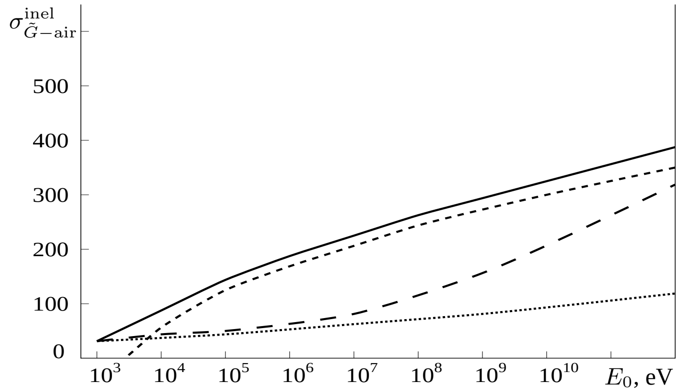

Fig. 3. The same as in Fig. 2 for $m_{\tilde{g}} = 50$ GeV.

ray data. The suitable modification of the model allowed to take into account all essential contributions to the interaction mechanism, to obtain a self-consistent description of interactions of gluino-containing particles with protons and nuclei, and to perform Monte-Carlo simulations of extensive air showers, initiated by gluino-particles in the atmosphere. In the current work we discuss in some detail the important features of interactions of $\tilde{g}$-hadrons as well as their impact on the calculated characteristics of air showers induced by such particles. In particular, we shall demonstrate that for the gluino mass being larger than 5 GeV the calculated longitudinal development of such showers appears to be in strong disagreement with the experimental observations, thus rejecting these particles as the UHE CR primaries.

2 QGSJET formalism for the interactions of $\tilde{g}$-hadrons

The QGSJET model, developed in the Gribov-Regge framework, treats hadronic interactions as multiple scattering processes, with different elementary scattering contributions corresponding either to pure "soft" nonperturbative dynamics, described phenomenologically as "soft" Pomeron exchanges, or to so-called "semihard" interactions. In the latter case at least a part of the underlying parton cascade develops in the region of large parton virtualities. This allows to apply the methods of perturbative QCD and leads to the concept of the "semihard" Pomeron (Kalmykov *et al.*, 1994; Ostapchenko *et al.*, 1997).

To include the new hadrons into this scheme one has to fix the value of the Pomeron-hadron coupling $\gamma_h \mathrm{P}$ and to define the momentum distribution of the constituent partons in the hadron. As the Pomeron couping is essentially proportional to the effective transverse size of the hadron $\gamma_h \mathrm{P} \sim R_h^2$, with the hadron h radius R_h being inverse proportional to its reduced mass $\tilde{M}_h$ (Berezinsky and Ioffe, 1986), in the particular case of the glueballino one can use simple scaling arguments to derive this parameter from that of the pion as

$$\gamma_{\tilde{G}} \mathrm{P} = \gamma_\pi \mathrm{P} \left(\frac{\tilde{M}_\pi}{\tilde{M}_{\tilde{G}}} \right)^2 . \qquad (1)$$

Here for the reduced mass of the glueballino, we use $\tilde{M}_{\tilde{G}} = m_{\tilde{g}} m_g / (m_{\tilde{g}} + m_g)$, with $m_{\tilde{g}}$ being the gluino mass and $m_g \simeq 0.7$ GeV is the constituent mass of the gluon. Similarly, for the pion we use $\tilde{M}_\pi = m_q/2$ with $m_q \simeq 0.35$ GeV as the quark constituent mass.

For the momentum distribution $\rho_{\tilde{g}}^{\tilde{G}}$ of the valence gluino in the glueballino we use the traditional Regge-inspired ansatz of the QGSJET model

$$\rho_{\tilde{g}}^{\tilde{G}}(x_{\tilde{g}}) \sim x_{\tilde{g}}^{\beta_{\tilde{g}}} (1 - x_{\tilde{g}})^{\beta_g} , \qquad (2)$$

with $\beta_g \simeq 0$. The unknown parameter $\beta_{\tilde{g}}$ can be fixed assuming that the energy is shared between the valence gluon and the valence gluino according to their constituent masses:

$$\langle x_{\tilde{g}} \rangle = \frac{m_{\tilde{g}}}{m_g + m_{\tilde{g}}} , \qquad (3)$$

where the average gluino momentum share is obtained from eq. (2) as $\langle x_{\tilde{g}} \rangle = (\beta_{\tilde{g}} + 1)/(\beta_g + \beta_{\tilde{g}} + 2)$.

In the case of gluino-hadrons, one has to account also for the contribution of the so-called "direct hard" process, where the valence gluino interacts perturbatively with some parton from the target hadron (nucleus). The specific feature of this interaction is that it results in very small energy losses of the valence gluino as a large longitudinal momentum transfer $z \simeq \frac{\Delta E_{\tilde{g}}}{E_{\tilde{g}}}$ is suppressed by the process kinematics, with the virtuality scale for the reaction increasing quadratically with z:

$$Q^2 = \frac{p_\perp^2}{1-z} + \frac{z^2 m_{\tilde{g}}^2}{1-z} , \qquad (4)$$

with $p_\perp$ and z being the transverse momentum and the light cone momentum fraction for the gluon emitted of the initial valence gluino (Berezinsky and Ioffe, 1986; Berezinsky and Kachelrieß, 1998).

To treat such interactions, the standard QGSJET procedure for the description of QCD parton evolution has been

Table 1. Inelasticity coefficient K_{h-air}^{inel} for hadron-air interactions at different energies E_0.

Reaction type	E_0, eV			
	10^{12}	10^{15}	10^{18}	10^{21}
p-air	0.65	0.74	0.79	0.83
$\tilde{G}-$air ($M_{\tilde{g}} = 2$ GeV)	0.26	0.28	0.29	0.29
$\tilde{G}-$air ($M_{\tilde{g}} = 5$ GeV)	0.15	0.15	0.16	0.16
$\tilde{G}-$air ($M_{\tilde{g}} = 50$ GeV)	0.02	0.02	0.02	0.02

generalized to include relevant processes for a supersymmetric parton (gluino). As the result, we developed the universal description of the interaction process, which allowed us both to calculate the interaction cross sections and to perform an explicit Monte Carlo modeling of glueballino-hadron (nucleus) collisions (Berezinsky *et al.*, 2001). Finally, we made simulations of $\tilde{G}$-induced air showers, using the traditional method based on the combination of numerical and Monte-Carlo techniques (Kalmykov *et al.*, 1997).

3 Numerical results

3.1 Interaction characteristics

In Fig. 1 we show the calculated cross sections σ_{h-air}^{inel} for inelastic interactions of protons, pions, and glueballinos with the nitrogen nucleus as the typical representative of the earth atmosphere. One can see from the figure that at high energies the glueballino cross sections $\sigma_{\tilde{G}-air}^{inel}$ are rather independent on the gluino mass and are comparable in magnitude with the corresponding cross sections for usual hadrons.

To investigate this result in more detail we plot in Fig. 2,3 the cross sections $\sigma_{\tilde{G}-air}^{inel}$ for $M_{\tilde{g}} = 5$ GeV and $M_{\tilde{g}} = 50$ GeV as calculated within different assumptions concerning the interaction mechanism: taking into account only pure ”soft” nonperturbative contributions to the interaction process [1] – ”soft”; accounting for both ”soft” and ”semihard” interactions but neglecting the contribution of the ”direct hard” process – ”semihard”; considering only the ”direct hard” contribution – ”hard”; and including all the mechanisms – ”total”. It is easy to see that, like in the case of usual hadrons, pure ”soft” processes give a small contribution at very high energies compared to the ”semihard” ones, characterized by a much steeper energy dependence. On the other hand, the ”direct hard” contribution is very essential in high energy glueballino interactions and even becomes the dominant one for large gluino masses – see Fig. 3, with the interaction process being essentially perturbative on the glueballino side. This important difference from the usual hadron case is due to the very asymmetric energy partition between parton constituents of the glueballino, with the valence gluino carrying almost the whole initial energy of the particle: 88% for $M_{\tilde{g}} = 5$ GeV and 99% for $M_{\tilde{g}} = 50$ GeV – see eq. (3).

[1] This option essentially corresponds to the basic assumptions of Albuquerque *et al.* (1999).

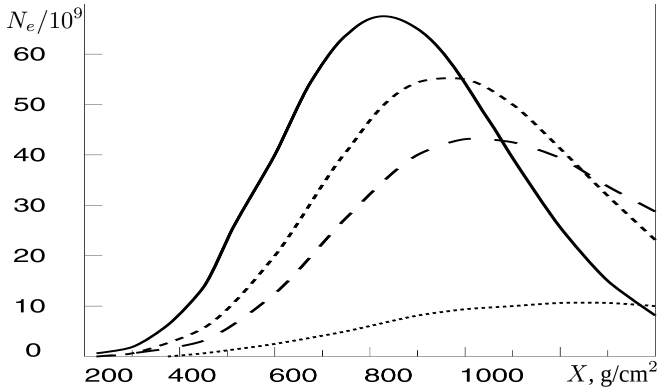

Fig. 4. Average shower profiles for proton- (smooth curve) and $\tilde{G}$-induced EAS ($m_{\tilde{g}} = 2$ GeV – dashed curve, $m_{\tilde{g}} = 5$ GeV – long-dashed, $m_{\tilde{g}} = 50$ GeV – dotted) of energy $E_0 = 10^{20}$ eV.

In Table 1 we present another important characteristics of $\tilde{G}$-air interaction, the so-called inelasticity coefficient, i.e. the relative energy loss of the glueballino in the process. It is compared with the corresponding quantity for proton-air interaction, defined as the relative energy difference between the initial proton and the fastest secondary baryon. Here one can see that the glueballino inelasticity, contrary to the proton case, remains essentially energy-independent and falls down rapidly with increasing gluino mass. The reason for this effect is twofold. On one side, as discussed above, gluinos of larger masses carry a larger fraction of the initial particle energy, leaving a smaller part of it for the sea constituents ((anti-)quarks and gluons) and thus reducing the average number of multiple interactions in $\tilde{G}$-air collisions. On the other hand, for heavier gluinos increases the relative weight of the ”direct hard” process, characterized by very small energy loss of the valence gluino.

3.2 Glueballino-induced extensive air showers

The two main features of the interaction – sufficiently large cross sections and small energy losses – result in a specific development of $\tilde{G}$-induced EAS: Contrary to the proton case, where the leading proton releases most of its energy in very few initial interactions at large heights, glueballino continues ejecting the energy in small portions into electromagnetic cascade throughout the atmosphere, resulting in a rather delayed EAS development and giving rise to a much wider shower profile compared to the one for the primary proton – Fig. 4.

We also compared the shape of the calculated profiles for individual p- and $\tilde{G}$-induced EAS of energy $E_0 = 3 \cdot 10^{20}$ eV with the corresponding measurements of the Fly’s Eye collaboration (Bird *et al.*, 1995) – Fig. 5. In doing so we choose only those showers which reach their maxima in the vicinity

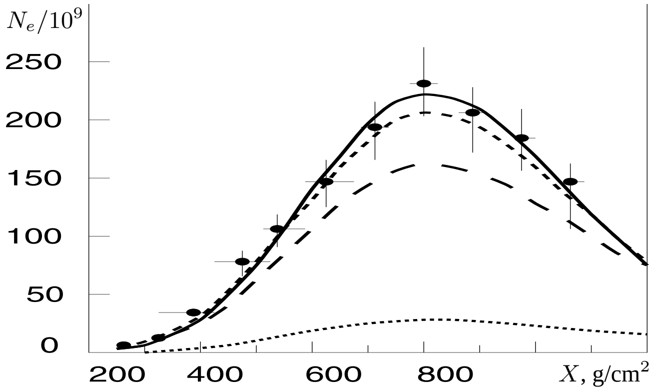

Fig. 5. "Individual" shower profiles for proton- and $\tilde{G}$-induced EAS of energy $E_0 = 3 \cdot 10^{20}$ eV. The abbreviations for the curves are the same as in Fig. 4. The Fly's Eye data (Bird *et al.*, 1995) are shown as filled circles.

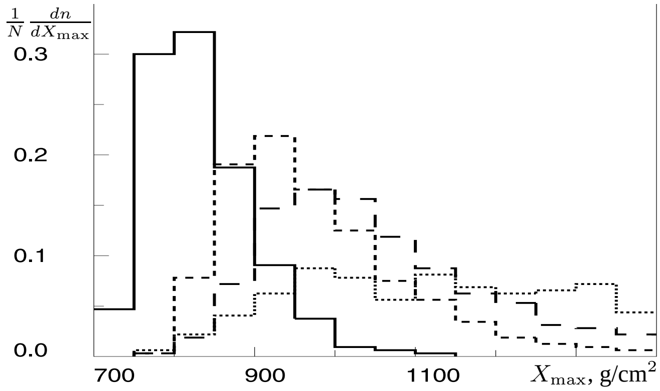

Fig. 6. Normalized distribution of the shower maxima for proton- (smooth histogram) and $\tilde{G}$-induced EAS ($m_{\tilde{g}} = 2$ GeV – dashed histogram, $m_{\tilde{g}} = 5$ GeV – long-dashed, $m_{\tilde{g}} = 50$ GeV – dotted) of energy $E_0 = 10^{20}$ eV.

of the measured value $X_{\max} = 815 \pm 50$ g/cm^2 and average the obtained profiles when shifting them to the same position of the shower maximum, $X_{\max} = 815$ g/cm^2. For gluino masses larger than 5 GeV the shape of the calculated profile strongly disagrees with the experimental observations, thus rejecting the corresponding particle as the cosmic ray primary. The account for the LPM effect results in only 5% reduction of the electron number in the shower maximum for proton-induced EAS (Kalmykov *et al.*, 1995) and has an even smaller influence on the $\tilde{G}$-induced showers due to much softer π^0-spectrum in the glueballino interactions.

In the case of the gluino mass being smaller than 5 GeV one can discriminate primary protons and primary gluino-hadrons analyzing the distributions of shower maxima – see Fig. 6. Such a possibility may be provided by the future data of the HIRES and AUGER installations.

4 Conclusions

We have analyzed the interactions of gluino-hadrons within the self-consistent Gribov-Regge framework, taking into account the contributions of both soft and semihard processes to the interaction mechanism. In particular, we have shown that the direct hard interaction of the valence gluino constitutes a substantial part of the total interaction cross section for such particles.

Comparing the calculated longitudinal development of extensive air showers, initiated by gluino-hadrons, with available experimental data we were able to obtain a new limit on the gluino mass, $m_{\tilde{g}} < 5$ GeV, for such particles to be initiators of very high energy cosmic ray events. Although our analysis was explicitly performed for the particular case of the glueballino as the test particle, our main results remain also valid for other hadronic states of the gluino as they are based on the general properties of hadronic systems containing a comparatively heavy gluino: i) small effective size of the system; ii) very asymmetric energy partition between parton constituents of gluino-hadrons; iii) significant interaction contribution of the "direct hard" gluino process, characterized by a small energy loss of the valence gluino. For sufficiently large gluino masses the whole interaction process becomes essentially perturbative on the gluino-hadron side, thus making our conclusions model-independent in this limit.

In the case of the gluino mass being smaller than 5 GeV one can finally confirm or reject the hypothesis of gluino-hadrons as the carriers of UHE CR signal on the basis of future measurements of ultra high energy extensive air showers with the HIRES and AUGER detectors.

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