Grand Unification Signal from Ultrahigh Energy Cosmic Rays?

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The spectrum of ultrahigh energy (above $\approx 10^9$ GeV) cosmic rays is consistent with the decay of grand unification scale particles. The predicted mass is $m_X = 10^b$ GeV, where $b = 14.6^{+1.6}_{-1.7}$.

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The interaction of protons with photons of the cosmic microwave background radiation (CMBR) predicts a sharp drop in the cosmic ray flux above the Greisen-Zatsepin-Kuzmin (GZK) cutoff around 5×10^{19} eV [1]. The available data show no such drop. About 20 events above 10^{20} eV were observed by experiments such as Akeno Giant Air Shower Array (AGASA) [2], Fly's Eye [3], Haverah Park [4], Yakutsk [5], and HiRes [6]. In the future, Pierre Auger [7] will have higher statistics.

Usually it is assumed that at these energies the galactic and extragalactic (EG) magnetic fields do not affect the orbit of the cosmic rays; thus they should point back to their origin within a few degrees. Though there are clustered events [8,9] the distribution is isotropic [10], which usually ought to be interpreted as a signature for EG origin.

Since above the GZK energy the attenuation length of particles is a few tens of megaparsecs [11–14], if an ultrahigh energy cosmic ray (UHECR) is observed on Earth it must be produced in our vicinity (except for UHECR scenarios based on weakly interacting particles, e.g., neutrinos [15]). Sources of EG origin (e.g., active galactic nuclei [16], topological defects [17], or the local supercluster [18]) should result in a GZK cutoff, which is in disagreement with experiments. It is generally believed [19] that there is no conventional astrophysical explanation for the observed UHECR spectrum.

An interesting idea suggested by Refs. [20,21] is that superheavy particles (SP) as dark matter could be the source of UHECRs. (Note that metastable relic SPs were proposed much earlier [22].) In [21] EG SPs were studied. Reference [20] made a crucial observation and analyzed the decay of SPs concentrated in the halo of our galaxy. They used the modified leading logarithmic approximation (MLLA) [23] for ordinary QCD and for supersymmetric QCD [24]. A good agreement of the EG spectrum with observations was noticed in [25]. Supersymmetric QCD is treated as the strong regime of the minimal supersymmetric standard model (MSSM). To describe the decay spectrum more accurately the HERWIG Monte Carlo program was used in QCD [26] and discussed in supersymmetric QCD [27,28], resulting in $m_X \approx 10^{12}$ GeV and $\approx 10^{13}$ GeV for the SP mass in SM and in MSSM, respectively.

SPs are very efficiently produced by the various mechanisms at postinflationary epochs [29]. Note that our analysis of SP decay covers a much broader class of possible sources. Several nonconventional UHECR sources (e.g., EG long ordinary strings [30] or galactic vortons [31], monopole-antimonopole pairs connected by strings [32]) produce the same UHECR spectra as decaying SPs.

In this Letter we study the scenario that the UHECRs are coming from decaying SPs and we determine the mass of this X particle m_X by a detailed analysis of the observed UHECR spectrum. We discuss both possibilities that the UHECR protons are produced in the halo of our galaxy and that they are of EG origin and their propagation is affected by CMBR. Here we do not investigate how they can be of halo or EG origin, we just analyze their effect on the observed spectrum instead. We assume that the SP decays into two quarks (other decay modes would increase m_X in our conclusion). After hadronization these quarks yield protons. The result is characterized by the fragmentation function (FF) $D(x, Q^2)$ which gives the number of produced protons with momentum fraction x at energy scale Q. For the proton's FF at present accelerator energies we use Ref. [33]. We evolve the FFs in ordinary [34] and in supersymmetric [35] QCD to the energies of the SPs. This result can be combined with the prediction of the MLLA technique, which gives the initial spectrum of UHECRs at the energy m_X. Altogether we study four different models: halo-SM, halo-MSSM, EG-SM, and EG-MSSM.

Reference [36] showed that both AGASA and Fly's Eye data demonstrated a change of composition, a shift from heavy—iron—at 10^{17} eV to light—proton—at 10^{19} eV. Thus the UHECRs are most likely to be dominated by protons, and in our analysis we use them exclusively.

The proton's FF can be determined from present experiments [33]. (Note that QCD event generators, e.g., HERWIG [37], predict the overall proton multiplicity correctly; however, they describe the large x region of the FF inaccurately.) The FFs at Q_0 energy scale are $D_i(x, Q_0^2)$, where i represents the different partons (quark/squark or gluon/gluino). The FFs cannot be determined perturbatively; however, their Q^2 evolution is given by the Dokshitzer-Gribov-Lipatov-Altarelli-Parisi equations [34]:

$$\frac{\partial D_i(x, Q^2)}{\partial \ln Q^2} = \frac{\alpha_s(Q^2)}{2\pi} \sum_j \int_x^1 \frac{dz}{z} P_{ji}(z, \alpha_s(Q^2)) \times D_j\left(\frac{x}{z}, Q^2\right). \tag{1}$$

One can interpret $P_{ji}(z)$, the splitting function, as the probability density that a parton i produces a parton j with momentum fraction z. Analogous evolution equations can be obtained by using coherent branching (angular ordering) for the emitted gluons [28,38]. We use this technique too. Results of direct Monte Carlo jet simulations are also available (cf. [39]). We solve the DGLAP equations numerically with the conventional QCD (SM case) splitting functions and with the supersymmetric (MSSM case) ones [35]. For the top and the MSSM partons we used the FFs of Ref. [28]. While solving the DGLAP equations, each parton is included at its own threshold energy. Table I shows all the FFs we used.

At small values of x, multiple soft gluon emission can be described by the MLLA [23]. This gives the shape of the total hadronic FF for soft particles (not distinguishing individual hadronic species) $xF(x,Q^2) \propto \exp[-\ln(x/x_m)^2/(2\sigma^2)]$, which is peaked at $x_m = \sqrt{\Lambda/Q}$ with $2\sigma^2 = A\ln^{3/2}(Q/\Lambda)$. According to [24] the values of A are $\sqrt{7/3}/6$ and $1/6$ for SM and MSSM, respectively. The MLLA describes the observed hadroproduction quite accurately in the small x region [40]. For large values of x the MLLA should not be used. We smoothly connect the solution for the FF obtained by the DGLAP equations and the MLLA result at a given x_c value. Our final result on m_X is rather insensitive to the choice of x_c; the uncertainty is included in our error estimate. We also determined the FF of the pion. Figure 1 shows the FF for the proton and pion at $Q = 10^{16}$ GeV in SM and MSSM.

UHECR protons produced in the halo of our galaxy can propagate practically unaffected and the production spectrum should be compared with the observations.

Particles of EG origin and energies above $\approx 5 \times 10^{19}$ eV lose a large fraction of their energies [1]. This effect can be described by the function $P(r,E,E_c)$, the probability that a proton created at a distance r with energy E arrives at Earth above the threshold energy E_c [41]. This function has been calculated for a wide range of parameters in [42], which we use in the present calculation. The original UHECR spectrum is changed by at least two different ways: (a) there should be a steepening due to the GZK effect; (b) particles losing their energy are accumulated just before the cutoff and produce a bump. We study the observed spectrum by assuming a uniform source distribution for UHECRs.

Our analysis includes the published and the unpublished UHECR data of [2–4,6]. Because of normalization difficulties we did not use the Yakutsk [5] results. We also performed the analysis using the AGASA data only and found the same value (well within the error bars) for m_X. Since the decay of SPs results in a non-negligible flux for lower energies $\log(E_{\min}/\mathrm{eV}) = 18.5$ is used as a lower end for the UHECR spectrum. Our results are insensitive to the definition of the upper end (the flux is extremely small there) for which we choose $\log(E_{\max}/\mathrm{eV}) = 26$. As is usual, we divided each logarithmic unit into ten bins. The integrated flux gives the total number of events in a bin. The uncertainties of the measured energies are about 30% which is one bin. Using a Monte Carlo method we included this uncertainty in the final error estimates. The predicted number of events in a bin is given by

$$N(i) = \int_{E_i}^{E^{i+1}} [AE^{-3.16} + Bj(E,m_X)], \qquad (2)$$

where E_i is the lower bound of the ith energy bin. The first term describes the data below 10^{19} eV according to [2], where the SP decay gives negligible contribution. The second one corresponds to the spectrum of the decaying SPs. A and B are normalization factors.

The expectation value for the number of events in a bin is given by Eq. (2) and it is Poisson distributed. To determine the most probable m_X value we used

TABLE I. The fragmentation functions of the different partons using the parametrization $D(x) = Nx^{\alpha}(1-x)^{\beta}$ at different energy scales (second column).

Flavor	Q (GeV)	N	α	β
$u = 2d$	1.41	0.402	−0.860	2.80
s	1.41	4.08	−0.0974	4.99
c	2.9	0.111	−1.54	2.21
b	9.46	40.1	0.742	12.4
t	350	1.11	−2.05	11.4
g	1.41	0.740	−0.770	7.69
$\tilde{q}_i, \tilde{g}$	1000	0.82	−2.15	10.8

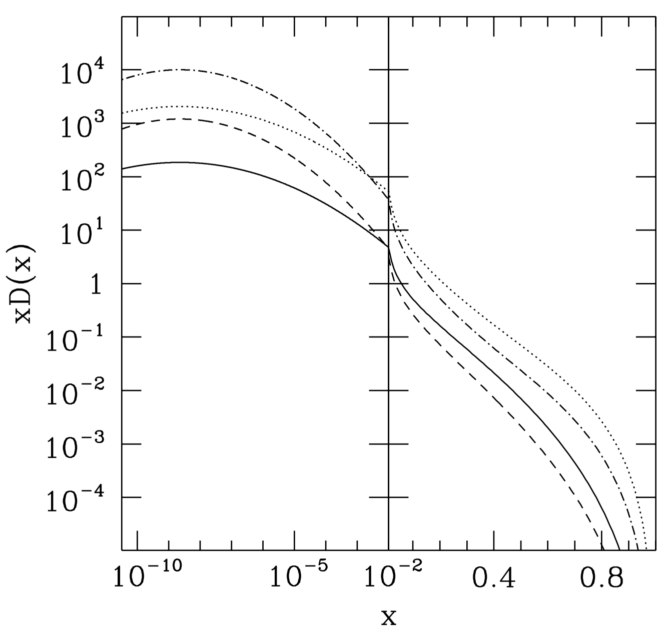

FIG. 1. The FFs averaged over the quark flavors at $Q = 10^{16}$ GeV for proton/pion in SM (solid/dotted lines) and in MSSM (dashed/dash-dotted lines) in the relevant x region. To show both the small and large x behavior we change from logarithmic scale to linear at $x = 0.01$.

the maximum-likelihood method by minimalizing the $\chi^2(A, B, m_X)$ for Poisson distributed data [43]

$$\chi^2 = \sum_{i=18.5}^{26.0} 2[N(i) - N_o(i) + N_o(i) \ln(N_o(i)/N(i))], \tag{3}$$

where $N_o(i)$ is the total number of observed events in the ith bin. In our fitting procedure we have three parameters: A, B, and m_X. The minimum of the $\chi^2(A, B, m_X)$ function is $\chi^2_{\min}$ at $m_{X\min}$ which is the most probable value for the mass, whereas $\chi^2(A', B', m_X) \equiv \chi^2_o(m_X) = \chi^2_{\min} + 1$ gives the one-sigma (68%) confidence interval for m_X. Here A', B' are defined in such a way that the $\chi^2(A, B, m_X)$ function is minimalized in A and B at fixed m_X. Figure 2 shows the measured UHECR spectrum and the best fit in the EG-MSSM scenario. The first bump of the fit represents particles produced at high energies and accumulated just above the GZK cutoff due to their energy losses. The bump at higher energy is a remnant of m_X. In the halo models there is no GZK bump, so the relatively large x part of the FF moves to the bump around 5×10^{19} GeV resulting in a much smaller m_X than in the EG case. An interesting feature of the GZK effect is that the shape of the produced GZK bump is rather insensitive to the injected spectrum so the dependence of χ^2 on the choice of the FF is small. The experimental data are far more accurately described by the GZK effect (dominant feature of the EG fit) than by the FF itself (dominant for halo scenarios).

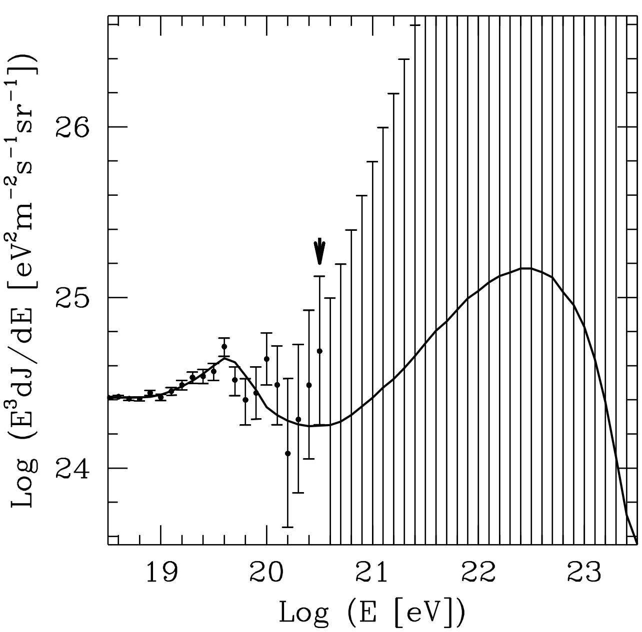

FIG. 2. The available UHECR data with their error bars and the best fit from a decaying SP. Note that there are no events above 3×10^{20} eV (shown by an arrow). Nevertheless, the experiments are sensitive even in this region. Zero event does not mean zero flux, but a well defined upper bound for the flux (given by the Poisson distribution). Therefore the experimental value of the integrated flux is in the "hatched" region with 68% confidence level. ("Hatching" is a set of individual error bars; though most of them are too large to be depicted in full.) Clearly, the error bars are large enough to be consistent with the SP decay.

To determine the most probable value for the mass of the SP we studied four scenarios. Figure 3 contains the $\chi^2_{\min}$ values and the most probable masses with their errors for these scenarios. (The uncertainties coming from the FFs are included in our error estimates on m_X.)

The UHECR data favors the EG-MSSM scenario. The goodnesses of the fits for the halo models are far worse. The SM and MSSM cases do not differ significantly. The most important message is that the masses of the best fits (EG cases) are compatible within the error bars with the MSSM gauge coupling grand unification scale [44].

The SP decay will also produce a huge number of pions which will decay into photons. Our spectrum contains 94% of pions and 6% of protons. This π/p ratio is in agreement with [12,45] which showed that for different classes of models $m_X \lesssim 10^{16}$ GeV, which is the upper boundary of our confidence intervals, the generated gamma spectrum is still consistent with the observational constraints. We performed the whole analysis including the pion produced γ-s in Eq. (3). The results agree with our results of Fig. 3 within error bars, which is easy to understand. For the EG case high energy γ-s dominate at energies where the observed flux is zero [25]. For the halo case the agreement has resulted by the similarity (except normalization) between D_p and D_π (cf. Fig. 1).

In the near future the UHECR statistics will probably be increased by an order of magnitude [7]. Performing our analysis for such a statistics, the uncertainty of m_X was found to be reduced by 2 orders of magnitude.

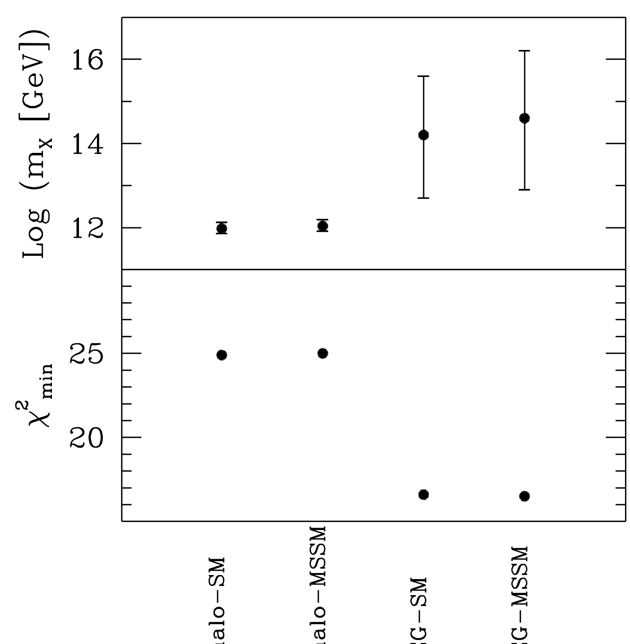

FIG. 3. The most probable values for the mass of the decaying ultraheavy dark matter with their error bars and the total χ^2 values. Note that 21 bins contain nonzero number of events and Eq. (2) has three free parameters.

Since the decay time should be at least the age of the universe it might happen that such SPs overclose the universe. Because of the large mass of the SPs a single decay results in a large number of UHECRs; thus a relatively small number of SPs can describe the observations. We checked that in all of the four scenarios the minimum density required for the best-fit spectrum is more than 10 orders of magnitude smaller than the critical one.

Details will be presented in a subsequent paper [46].

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[1] K. Greisen, Phys. Rev. Lett. **16**, 748 (1966); G. T. Zatsepin and V. A. Kuzmin, Pis'ma Zh. Eksp. Teor. Fiz. **4**, 114 (1966).

[2] M. Takeda *et al.,* Phys. Rev. Lett. **81**, 1163 (1998); astro-ph/9902239; www-akeno.icrr.u-tokyo.ac.jp/AGASA/.

[3] D. J. Bird *et al.,* Phys. Rev. Lett. **71**, 3401 (1993); Astrophys J. **424**, 491 (1994); **441**, 144 (1995).

[4] M. A. Lawrence, R. J. O. Reid, and A. A. Watson, J. Phys. G **17**, 773 (1991).

[5] N. N. Efimov *et al.,* in *Proceedings of the Astrophysical Aspects of the Most Energetic Cosmic Rays,* edited by M. Nagano and F. Takahara (World Scientific, Singapore, 1991).

[6] D. Kieda *et al.,* in *Proceedings of the 26th International Cosmic Ray Conference, Salt Lake, 1999* (AIP, New York, 2000); www.physics.utah.edu/Resrch.html.

[7] M. Boratav, Nucl. Phys. Proc. **48**, 488 (1996); C. K. Guerard, *ibid.* **75A**, 380 (1999); X. Bertou, M. Boratav, and A. Letessier-Selvon, Int. J. Mod. Phys. A **15**, 2181 (2000).

[8] N. Hayashida *et al.,* Phys. Rev. Lett. **77**, 1000 (1996).

[9] Y. Uchihori *et al.,* Astropart. Phys. **13**, 151 (2000).

[10] S. L. Dubovski and P. G. Tinyakov, JETP Lett. **68**, 107 (1998); V. Berezinsky and A. A. Mikhailov, Phys. Lett. B **449**, 61 (1999); C. A. Medina Tanco and A. A. Watson, Astropart. Phys. **12**, 25 (1999).

[11] S. Yoshida and M. Teshima, Prog. Theor. Phys. **89**, 833 (1993); F. A. Aharonian and J. W. Cronin, Phys. Rev. D **50**, 1892 (1994); R. J. Protheroe and P. Johnson, Astropart. Phys. **4**, 253 (1996).

[12] P. Bhattacharjee and G. Sigl, Phys. Rep. **327**, 109 (2000).

[13] A. Achterberg *et al.,* astro-ph/9907060.

[14] T. Stanev *et al.,* Phys. Rev. D **62**, 093005 (2000).

[15] G. Domokos and S. Nussinov, Phys. Lett. B **187**, 372 (1987); D. Fargion, B. Mele, and A. Salis, Astrophys. J. **517**, 725 (1999); T. J. Weiler, Astropart. Phys. **11**, 303 (1999); **12**, 379(E) (2000); G. Domokos and S. Kovesi-Domokos, Phys. Rev. Lett. **82**, 1366 (1999).

[16] P. L. Biermann and P. A. Strittmatter, Astrophys. J. **322**, 643 (1987).

[17] C. T. Hill, D. N. Schramm, and T. P. Walker, Phys. Rev. D **36**, 1007 (1987); P. Bhattacharjee, C. T. Hill, and D. N. Schramm, Phys. Rev. Lett. **69**, 567 (1992); G. Sigl, astro-ph/9611190; V. Berezinsky and A. Vilenkin, Phys. Rev. Lett. **79**, 5202 (1997).

[18] V. S. Berezinsky and S. I. Grigorieva, in *Proceedings of the 16th International Cosmic Ray Conference, Kyoto, 1979* (Institute for Cosmic Ray Research, University of Tokyo, Tokyo, Japan, 1979), Vol. 2, p. 81.

[19] R. D. Blandford, Phys. Scr. **T85**, 191 (2000).

[20] V. Berezinsky, M. Kachelrieß, and A. Vilenkin, Phys. Rev. Lett. **79**, 4302 (1997).

[21] V. A. Kuzmin and V. A. Rubakov, Phys. At. Nucl. **61**, 1028 (1998).

[22] J. Ellis *et al.,* Phys. Lett. B **247**, 257 (1990); Nucl. Phys. **B373**, 399 (1992); P. Gondolo, G. B. Gelmini, and S. Sarkar, Nucl. Phys. **B392**, 111 (1993).

[23] Ya. I. Azimov, Yu. L. Dokshitzer, V. A. Khoze, and S. I. Troyan, Phys. Lett. **165B**, 147 (1985); Z. Phys. C **27**, 65 (1985); **31**, 213 (1986); C. P. Fong and B. R. Webber, Nucl. Phys. **B355**, 54 (1991).

[24] V. Berezinsky and M. Kachelrieß, Phys. Lett. B **434**, 61 (1998).

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

[26] M. Birkel and S. Sarkar, Astropart. Phys. **9**, 297 (1998).

[27] S. Sarkar, hep-ph/0005256.

[28] N. Rubin, www.stanford.edu/~nrubin/Thesis.ps.

[29] For a review see V. Berezinsky, astro-ph/0001163.

[30] G. Vincent, N. Antunes, and M. Hindmarsh, Phys. Rev. Lett. **80**, 2277 (1998); M. Hindmarsh, hep-ph/9806469.

[31] L. Masperi and G. Silva, Astropart. Phys. **8**, 173 (1998).

[32] J. J. Blanco-Pillado and K. D. Olum, Phys. Rev. D **60**, 083001 (1999).

[33] J. Binnewies, B. A. Kniehl, and G. Kramer, Phys. Rev. D **52**, 4947 (1995); B. A. Kniehl, G. Kramer, and B. Potter, Phys. Rev. Lett. **85**, 5288 (2000); Nucl. Phys. **B582**, 514 (2000).

[34] V. N. Gribov and L. N. Lipatov, Sov. J. Nucl. Phys. **15**, 438 (1972); L. N. Lipatov, *ibid.* **20**, 94 (1975); G. Altarelli and G. Parisi, Nucl. Phys. **B126**, 298 (1977); Yu. L. Dokshitzer, Sov. Phys. JETP **46**, 641 (1977).

[35] S. K. Jones and C. H. Llewellyn Smith, Nucl. Phys. **B217**, 145 (1983).

[36] B. R. Dawson, R. Meyhandan, and K. M. Simpson, Astropart. Phys. **9**, 331 (1998).

[37] G. Marchesini *et al.,* Comput. Phys. Commun. **67**, 465 (1992).

[38] G. Marchesini and B. R. Webber, Nucl. Phys. **B330**, 261 (1990); S. Catani, B. R. Webber, and G. Marchesini, Nucl. Phys. **B349**, 635 (1991).

[39] V. Berezinsky and M. Kachelriess, Phys. Rev. D **63**, 034007 (2001).

[40] See, e.g., P. Abreu *et al.,* Phys. Lett. B **459**, 397 (1999); G. Abbiendi *et al.,* Eur. Phys. J. C **16**, 185 (2000).

[41] J. N. Bahcall and E. Waxman, Astrophys. J. **542**, 542 (2000).

[42] Z. Fodor and S. D. Katz, Phys. Rev. D **63**, 023002 (2001).

[43] C. Caso *et al.,* Eur. Phys. J. C **3**, 172 (1998).

[44] U. Amaldi, W. de Boer, and H. Furstenau, Phys. Lett. B **260**, 447 (1991).

[45] G. Sigl, S. Lee, P. Bhattacharjee, and S. Yoshida, Phys. Rev. D **59**, 043504 (1999).

[46] Z. Fodor and S. D. Katz (to be published).