Ultrahigh energy cosmic rays as a Grand Unification signal

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Abstract

We analyze the spectrum of the ultrahigh energy (above $\approx 10^9$ GeV) cosmic rays. With a maximum likelihood analysis we show that the observed spectrum is consistent with the decay of extragalactic GUT scale particles. The predicted mass for these superheavy particles is $m_X = 10^b$ GeV, where $b = 14.6^{+1.6}_{-1.7}$.

1 Introduction

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 $5 \cdot 10^{19}$ eV (Greisen, 1966; Zatsepin and Kuzmin, 1966). The available data shows no such drop. About 20 events above 10^{20} eV were observed by experiments such as AGASA (Takeda et al., 1998), Fly's Eye (Bird et al., 1993), Haverah Park (Lawrence et al., 1991), Yakutsk (Efimov et al., 1991) and HiRes (Kieda et al., 1999). Future experiments, particularly Pierre Auger (Boratav, 1996; Guerard, 1999; Bertou et al. 2000), will have a much 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 (Hayashida et al., 1996; Uchihori et al., 2000) the overall distribution is practically isotropic (Dubovski and Tinyakov, 1998; Berezinsky and Mikhailov, 1999; Medina Tanco and Watson, 1999), 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 (Yoshida and Teshima, 1993 ; Aharonian and Cronin, 1994; Protheroe and Johnson, 1996; Bhattacharjee and Sigl, 2000; Achterberg et al., 1999; T. Stanev et al., 2000) if an ultrahigh energy cosmic ray (UHECR) is observed on Earth it must be produced in our vicinity. Sources of EG origin should result in a GZK cutoff, which is in disagreement with experiments. It is generally believed that there is no conventional astrophysical explanation for the observed UHECR spectrum.

An interesting idea is that superheavy particles (SP) as dark matter could be the source of UHECRs. In (Kuzmin and Rubakov, 1998) EG SPs were studied. A crucial observation was made (Berezinsky et al., 1997) about the decay of SPs concentrated in the halo of our galaxy. They used the modified leading logarithmic approximation (MLLA) (Azimov et al., 1985; Fong and Webber 1991) for ordinary QCD and for supersymmetric QCD (Berezinsky and Kachelrieß, 1998). A good agreement of the EG spectrum with observations was noticed in (Berezinsky et al., 1998). Supersymmetric QCD is treated as the strong regime of the minimal supersymmetric standard model (MSSM). To describe the decay spectrum more accurately HERWIG Monte-Carlo (Marchesini et al., 1992) was used in QCD (Birkel and Sarkar, 1998) and discussed in supersymmetric QCD (Rubin 1999, Sarkar 2000), 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 post inflatory epochs (for a review see Berezinsky 2000). Note, that any analysis of SP decay covers a much broader class of possible sources. Several non-conventional UHECR sources produce the same UHECR spectra as decaying SPs.

Here 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 can they 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 present accelerator energies can be used (Binnenwies et al., 1995; Kniehl et al., 2000). We evolve the FFs in ordinary (Gribov and Lipatov 1972; Lipatov 1975; Altarelli and Parisi, 1977; Dokshitzer, 1977) and in supersymmetric (Jones and Llewellyn Smith 1983) 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.

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

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

2 Decay and fragmentation of heavy particles

The UHECRs are most likely to be dominated by protons (Dawson et al., 1998); in our analysis we use them exclusively.

The FF of the proton can be determined from present experiments (Binnenwies et al., 1995; Kniehl et al., 2000). 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 can not be determined in perturbative QCD; however, their evolution in Q^2 is governed by the DGLAP equations (Gribov and Lipatov 1972; Lipatov 1975; Altarelli and Parisi, 1977; Dokshitzer, 1977):

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

where $P_{ji}(z)$ is the splitting function. We solve the DGLAP equations numerically with the conventional QCD (SM case) splitting functions and with the supersymmetric (MSSM case) ones (Jones and Llewellyn Smith 1983). For the top and the MSSM partons we used the FFs of ref. (Rubin 1999). While solving the DGLAP equations each parton is included at its own threshold energy.

At small values of x, multiple soft gluon emission can be described by the MLLA. It describes the observed hadroproduction quite accurately in the small x region (see eg. Abreu et al., 1999; Abbiendi et al., 2000). 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. Fig. 1 shows the FF for the proton and pion at $Q = 10^{16}$ GeV in SM and MSSM.

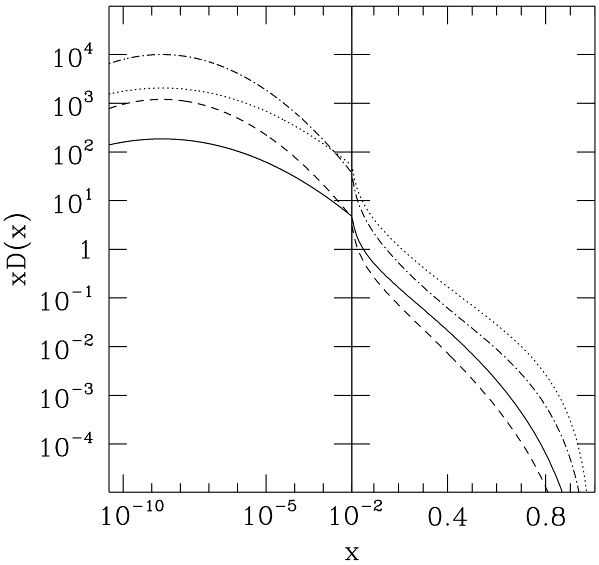

Figure 1: The FFs averaged over the quark flavors at $Q = 10^{16}$ GeV for proton/pion in SM (solid/dotted line) and in MSSM (dashed/dashed-dotted line) in the relevant x region. To show both the small and large x behavior we change from logarithmic scale to linear at $x = 0.01$.

3 Comparison of the predicted and the observed spectra

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

Particles of EG origin and energies above $\approx 5 \cdot 10^{19}$ eV loose a large fraction of their energies due to interactions with CMBR (Greisen, 1966; Zatsepin and Kuzmin, 1966). This effect can be quantitatively 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 (Bahcall and Waxman 2000). This function has been calculated for a wide range of parameters in (Fodor and Katz, 2001a), which we use in the present calculation. The original UHECR spectrum is changed at least by two different ways: (a) there should be a steepening due to the GZK effect; (b) particles loosing 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 (from the www pages of the experiments) UHECR data of AGASA, Fly's Eye, Haverah Park and HiRes. Since the decay of SPs results in a non-negligible flux for lower energies $\log(E_{min}/\text{eV}) = 18.5$ 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

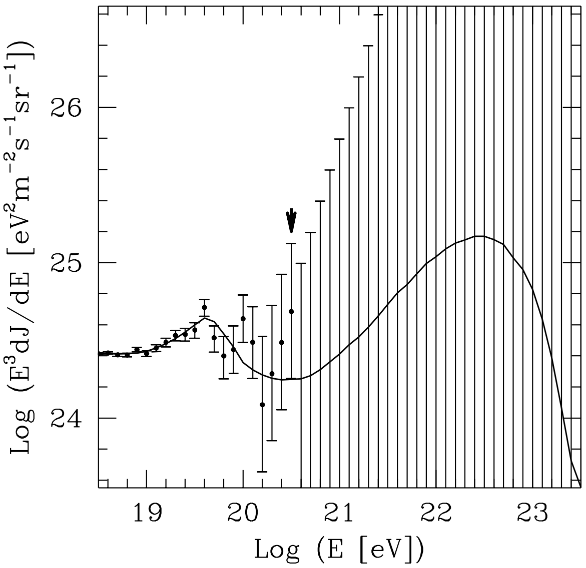

Figure 2: The available UHECR data with their error bars and the best fit from a decaying SP. Note that there are no events above 3×10^{20} eV (shown by an arrow). Nevertheless the experiments are sensitive even in this region. Zero event does not mean zero flux, but a well defined upper bound for the 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.

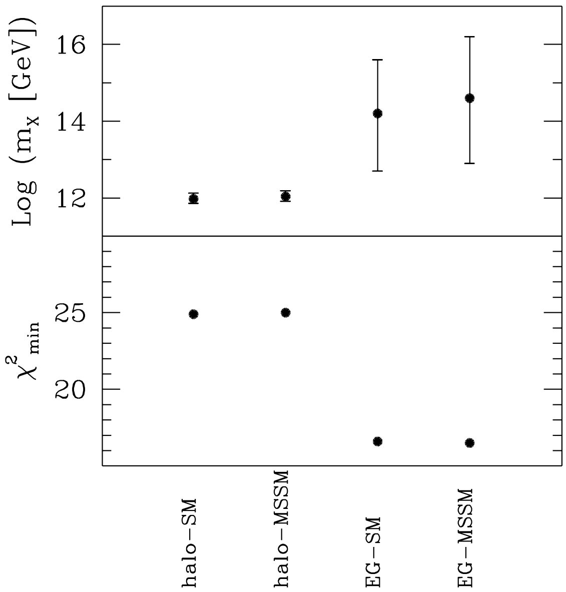

Figure 3: The most probable values for the mass of the decaying ultra heavy dark matter with their error bars and the total χ^2 values. Note that 21 bins contain nonzero number of events and eqn.(2) has 3 free parameters.

choose $\log(E_{max}/\text{eV}) = 26$. As it is usual we divided each logarithmic unit into ten bins. 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

$$N(i) = \int_{E_i}^{E^{i+1}} \left[A \cdot E^{-3.16} + B \cdot j(E, m_X)\right], \quad (2)$$

where E_i is the lower bound of the ith energy bin. The first term describes the data below 10^{19} eV according to (Takeda et al., 1998), 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 eqn. (2) and it is Poisson distributed. To determine the most probable m_X value we used the maximum-likelihood method by minimalizing the $\chi^2(A, B, m_X)$ for Poisson distributed data (Groom et al., 2000)

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

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. Fig. 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. The experimental data is far more accurately described by the GZK effect (dominant feature of the EG fit) than by the FF itself (dominant for halo scenarios).

4 Results

To determine the most probable value for the mass of the SP we studied 4 scenarios. Fig. 3 contains the χ^2_{min} values and the most probable masses with their errors for these scenarios.

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 unification GUT scale (Amaldi at al., 1991).

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 (Bhattacharjee and Sigl, 2000; Bhattacharjee and Sigl, 2000) 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 eqn. (3). The results agree with our results of Fig. 3 within errorbars.

In the near future the UHECR statistics will probably be increased by an order of magnitude (Boratav, 1996; Guerard, 1999; Bertou et al. 2000). Performing our analysis for such a statistics the uncertainty of m_X was found to be reduced by two orders of magnitude.

Since the decay time should be at least the age of the universe it might happen that such SPs overclose the universe. Due to 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 ten orders of magnitude smaller than the critical one.

More details of the present analysis can be found in (Fodor and Katz, 2001b). Note, that a similar study based on the Z-burst scenario (Fargion et al., 1999; Weiler, 1999) can be carried out which gives the mass of the heaviest neutrino (Fodor et al., 2001).

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