Gamma Rays from Super-Heavy Relic Particles in the Halo

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Abstract

Superheavy (SH) quasistable particles generated in the Early Universe could be responsable for Ultra High Energy Cosmic Rays (UHECR) and be a component of Cold Dark Matter (CDM) in the universe. These particles are likely to cluster in the galactic halo, so that the main part of UHECR are gamma rays produced in the decay of neutral pions. Charged pions are also produced in the same process and result in high energy electrons. We consider here the production of gamma rays by synchrotron emission of these electrons in the galactic magnetic field. The gamma ray fluxes are in the region of interest for some current and proposed experiments (e.g. EGRET, GLAST, MILAGRO) in the energy range $0.1-10^4$ GeV. A comparison with the existing upper limits at 10^5-10^8 GeV is also carried out. The detection of this flux of gamma rays would be an important signature of SH relic particles as sources of UHECR and would give a clue to the physics of the Early Universe.

I. INTRODUCTION

The detection of cosmic rays well above 10^{20} eV poses a serious challenge to our understanding of the acceleration processes as well as of the propagation of these particles from the sources. Particles with $E \geq 10^{19}$ eV are thought to be of extragalactic origin since the galactic magnetic field is unable to confine and isotropize them. However if the sources are cosmological then the UHECR spectrum would have as a unique signature the presence of a pronounced cutoff (the so called GZK cutoff [2]) at $E \sim 5 \cdot 10^{19}$ eV, which is not observed (see [1] for a recent discussion). This limits the distance to the sources of UHECR to be less than ~ 50 Mpc and no plausible source has been identified by current experiments within this distance, unless very large deflection angles are assumed, which looks incompatible with the current limits on the intergalactic magnetic field (see [3] for a review and [4] for revised limits in a inhomogeneous universe).

The lack of counterparts to the observed events, together with the difficulty of the known acceleration mechanisms to reach the observed energies, prompted a new class of models (top-down models) (for a recent review see [5] and references therein) where UHECR are produced by the decay of grand unification massive bosons (generically named X-particles) with mass $m_X \sim 10^{13} - 10^{16}$ GeV. These X-particles can either be produced in processes involving topological defects (TD) or by the decay of SH quasistable (lifetime τ much larger than the age of the Universe t_0) particles relics of the early universe [6–10] in the assumption that they represent some fraction of the CDM.

In the latter case, the UHECR spectrum is dominated by the halo component and hence it has no GZK cutoff. Signatures of this model have been discussed in [12], where it was pointed out that if UHECR above $\sim 10^{19}$ eV are produced in the halo by the decay of X-particles, then the flux should be dominated by gamma rays produced by the decay of neutral pions from the hadronic cascade initiated by ultra high energy partons ($X \to q\bar{q}$, $q \to$ hadrons). The model is also characterized by some degree of anisotropy due to the asymmetric position of the sun in the galaxy [11–13].

Together with neutral pions charged pions are also generated which in turn decay into electrons and positrons (hereafter we shall call them both electrons) and neutrinos.

In this paper we calculate the flux of gamma rays which is produced by synchrotron emission of the electrons in the galactic magnetic field when the density of SH particles in the halo is normalized to fit the observed UHECR flux. Our calculations show that in most of the cases the predicted gamma ray emission is compatible with the upper limits imposed by experiments like HEGRA, EASTOP, CASA-MIA and Utah-Michigan at $10^5 - 10^8$ GeV and, in the energy range $0.1 - 10^4$ GeV might be detectable by future experiments like GLAST.

The paper is planned as follows: in section II we present a benchmark calculation where we estimate the magnitude of the gamma ray flux from ultra high energy electrons (UHEE) in the galactic magnetic field. In section III we introduce the fragmentation functions both for ordinary QCD and in the supersymmetric generalization proposed in [14]. Our conclusions are presented in section IV.

II. AN ESTIMATE OF THE EFFECT

The SH particles we are interested in are quasistable, which means that their lifetime τ_X is much larger than the age t_0 of the Universe. If n_0 is the average density of SH particles with mass m_X in the halo, the decay rate can be estimated as $\dot{n}_X^{halo} \approx n_0/\tau_X$. The decay of an X-particle typically results in the production of a quark-antiquark pair

$$X \to q\bar{q}$$

and each quark produces a jet of hadrons (mainly Nucleons (N) and pions (π)) with total energy in the jet $E_{jet} = m_X/2$. The hadron spectrum is given by the fragmentation function $W_i(x, m_X)$ where $i = N, \pi$ and $x = E_i/E_{jet} = 2E_i/m_X$. Many discussions can be found in the recent literature about approximations to the fragmentation function and extrapolations of the low energy phenomenological expressions to the extremely large center of mass energy involved in the production of UHECR by the decay of X-particles (for a recent review see [5]; a numerical approach involving the use of a QCD event generator was used in [7]). We address this problem in the next section, while here we shall use a very simple approximation proposed in [15,16] and valid for $x \ll 1$. In this approach the spectrum of the pions, which represent most of the content of the jet, is given by

$$\frac{dN_\pi}{dx} = \frac{15}{16} x^{-3/2}(1-x)^2 \approx \frac{15}{16} x^{-3/2} \quad x \ll 1. \tag{1}$$

The spectrum of the nucleons has the same form as in eq. (1) but the normalization is such that the ratio N/π in the jet is ~ 0.05 as suggested by the decay $Z_0 \to hadrons$ at LEP. Moreover each pion family will take approximately 1/3 of the total pion content in the jet.

The small N/π ratio at the production implies that on galactic distance scales the flux of UHECR produced by the decay of X-particles is dominated by the gamma rays produced in the decay of neutral pions. Therefore, in the following we shall estimate the rate $\dot{n}_X^{halo}$ of decay, requiring that the flux of gamma rays equals the flux of UHECR at some energy. For the sake of simplicity we shall also assume here that the SH particles are distributed homogeneously in the halo whose size is R_H. The flux of gamma rays with energy E_γ at the Earth is then easily derived to be

$$I_\gamma^{UHE}(E_{UHE}) = 2 \times \frac{1}{3} \dot{n}_X^{halo} \frac{R_H}{4\pi} \int_{E_{UHE}}^{E_{jet}} dE_\pi \frac{dN_\pi}{dE_\pi} \frac{2}{E_\pi} \;=\; \frac{5}{6} \dot{n}_X^{halo} \frac{R_H}{4\pi} \left(\frac{m_X}{2}\right)^{1/2} E_{UHE}^{-3/2}, \tag{2}$$

where the factor 2 in front takes into account the two jets and the factor 1/3 accounts for the π^0's only. Moreover we used $dN_\pi/dE_\pi = (2/m_X) dN_\pi/dx$.

The comparison of our prediction with the observed flux of UHECR at $E = 10^{10}$ GeV immediately gives

$$\dot{n}_X^{halo} \approx 1.8 \cdot 10^{-42} \left(\frac{m_X}{10^{14} GeV}\right)^{-1/2} \left(\frac{R_H}{100 kpc}\right) cm^{-3} s^{-1}. \tag{3}$$

A fraction 2/3 of the energy in the jet is transformed into charged pions which contribute an electron flux through production and decay of muons. The density spectrum of these electrons can be calculated in the standard way (muon decay) and gives

$$q_e(E_e) = \frac{40}{63}\dot{n}_X^{halo}\frac{m_\pi^3 - m_\mu^3}{m_\pi^2 - m_\mu^2}\frac{1}{m_\pi}\left(\frac{m_X}{2}\right)^{1/2} E_e^{-3/2}. \quad (4)$$

The ultra high energy electrons from pion decay are produced in the magnetic field of our galaxy, whose average strength will be denoted here by B_μ (in μG). The synchrotron emission of these electrons will typically result in the production of photons with energy

$$E_\gamma = 1.5 \cdot 10^3 B_\mu \left(\frac{E_e}{10^{10} GeV}\right)^2 \ GeV. \quad (5)$$

Electrons with energy $E_e \geq 10^{17}$ eV will then radiate photons with energy $E_\gamma \geq 0.1$ GeV. Here we estimate the flux of these photons. The synchrotron emission is the dominant channel of energy losses at the energies of interest, and the time for losses is so small that all the electron energy is very rapidly radiated in the form of gamma rays, with flux

$$I_\gamma(E_\gamma) = \frac{R_H}{4\pi} q_e(E_e)\frac{E_e}{E_\gamma}\frac{dE_e}{dE_\gamma} = 1.2 \cdot 10^{33}\left(\frac{m_X}{10^{14} GeV}\right)^{1/2} \dot{n}_X^{halo} B_\mu^{-1/4}\left(\frac{R_H}{100kpc}\right) E_\gamma^{-7/4} cm^{-2} GeV^{-1} s^{-1} sr^{-1} \quad (6)$$

where $\frac{dE_e}{dE_\gamma}$ has been derived from eq. (5). The normalized flux of gamma rays can now be calculated using eq. (3) which gives the following very interesting result

$$I_\gamma(E_\gamma) = 2.1 \cdot 10^{-9} B_\mu^{-1/4} E_\gamma^{-7/4} \ cm^{-2} GeV^{-1} s^{-1} sr^{-1} \quad (7)$$

independent on the size of the halo R_H and the mass of the X-particles m_X.

The result is also weakly dependent on the average magnetic field B_μ. For $B_\mu \sim 0.1$–$1\ \mu G$ the flux derived from eq. (7) turns out to be detectable by EGRET in the energy range 100 MeV$\leq E_\gamma \leq$ few GeV.

The inverse dependence of I_γ on B_μ can be easily explained on the basis of the electron spectrum resulting from the fragmentation function: such spectrum contains most of the energy at high electron energies. Therefore, at fixed E_γ the larger electron energies (correspondent to smaller magnetic fields) contribute more, as far as the required electron energies are below $m_X/2$.

The result quoted in eq. (7) changes appreciably as a function of the energy where SH relic particles provide the main contribution to the UHECR flux. This is more evident if we combine eqs. (2) and (6) to give:

$$I_\gamma(E_\gamma) = 8.2 \cdot 10^3 I_\gamma^{UHE}(E_{UHE}) E_{UHE}^{3/2} B_\mu^{-1/4} E_\gamma^{-7/4}, \tag{8}$$

where now E_{UHE} is the energy at which we normalize the UHECR flux I_γ^{UHE} (measured in units of $cm^{-2}s^{-1}sr^{-1}GeV^{-1}$). From eq. (8) it results that if the normalization is carried out at $5 \cdot 10^{10}$ GeV, then the numerical factor in eq. (7) is ~ 18 times smaller. In this case, for $B_\mu \sim 1$ the flux drops below the detectability level of EGRET, though it remains still in the detectability range of next generation satellites (e.g. GLAST).

Let us come now to another interesting point: following the approach used in [14] and [12], the rate of decay of SH particles in the halo may be used to normalize the same quantity in the extragalactic space, through the relation

$$\frac{\dot{n}_X^{halo}}{\dot{n}_{eg}} = \frac{\rho_{CDM}^{halo}}{\Omega_{CDM}\rho_{cr}} \tag{9}$$

where $\dot{n}_{eg}$ is now the rate of X particle decay in the extragalactic space, $\rho_{CDM}^{halo} = 0.3$ GeVcm^{-3} is the energy density of CDM in the halo, Ω_{CDM} is the fraction of CDM and ρ_{cr} is the critical density of the Universe. We shall adopt here $\Omega_{CDM}h^2 = 0.2$. If we call B_μ^{eg} (in μG) the extragalactic magnetic field, the flux of gamma rays due to the synchrotron emission of UHEE can be calculated similarly to eq. (6) with R_H substituted by ct_0, where $t_0 = 2.06 \cdot 10^{17} h^{-1} s$ is the age of the Universe and h is the dimensionless Hubble constant. Of course this treatment is valid as far as gamma rays are not absorbed on scales much smaller than ct_0, which limits this estimate to $E_\gamma < 500 - 1000$ GeV. In this assumption the ratio of gamma rays with energy E_γ produced in the extragalactic space relative to the ones produced in the halo is given by

$$\frac{I_\gamma^{eg}(E_\gamma)}{I_\gamma(E_\gamma)} = 0.23 \left(\frac{R_H}{100kpc}\right)^{-1} \left(\frac{\Omega_{CDM}h^2}{0.2}\right) \left(\frac{B_\mu}{B_\mu^{eg}}\right)^{1/4}, \tag{10}$$

where we used $h = 0.6$. For extragalactic magnetic fields of order $10^{-9} - 10^{-10}$ Gauss, and a typical galactic field of order of μG, the two gamma ray fluxes are comparable. Unfortunately only upper limits are currently available on the extragalactic magnetic field. Therefore in the following we shall not consider the extragalactic flux in any more detail and we shall concentrate our attention on the gamma ray flux from the halo.

III. A DETAILED CALCULATION

The simple calculations presented in the previous section suggest that the synchrotron emission of UHEE in the galactic magnetic field can produce an interesting flux in high energy gamma rays. The rate of production of electrons is normalized by requiring that the gamma rays generated in the decay of neutral pions saturate the flux of UHECR above some energy. In this section we directly use as normalization point $5 \cdot 10^{19}$ eV, rather than the 10^{19} eV used before, mainly inspired by two factors: 1) using more realistic fragmentation functions and normalizing our gamma ray fluxes at 10^{19} eV it is easy to overproduce the UHECR at higher energy; 2) in the same conditions the flux of primary gamma rays can easily exceed the CASA-MIA limits at $\sim 10^8$ GeV. As a consequence of this more conservative approach, the fluxes that will be derived here will be appreciably smaller than the ones derived in the previous bentchmark calculation, and can be considered as a lower limit prediction.

As first pointed out in [6] and [12] the UHECR flux in this halo model is the generation spectrum resulting from the initial fragmentation process, hence it is dominated by gamma rays with respect to nucleons.

In this section we assume, following [12], that the rate of particle production is parametrized as the dark matter distribution [17]:

$$\dot{n}_X^h(R) = \frac{\dot{n}_0^h}{(R/r_0)^\gamma \left[1 + (R/r_0)^\alpha\right]^{(\beta-\gamma)/\alpha}} \tag{11}$$

where $\dot{n}_0^h$ is the normalization rate, R is the distance to the galactic center and r_0 is a distance scale between 5 and 10 kpc. The parameters $\alpha, \beta, \gamma = (2, 2, 0)$ correspond to an isothermal profile, while $\alpha, \beta, \gamma = (2, 3, 0.2)$ give the best fit to observational data [17] and finally $\alpha, \beta, \gamma = (1, 3, 1)$ are obtained in the numerical simulation of ref. [18].

The calculation of the spectrum of hadrons produced in a single X-particle decay is given by the fragmentation function for the process $q \to hadrons$. The fragmentation functions we use here are the MLLA limiting spectrum of ordinary QCD [19] and its supersymmetric generalization given in [14] (hereafter SUSY-QCD). In the first case the fraction of pions produced in a single event is taken as $f_\pi \approx 1$, while in the second case we take, according with [14], $f_\pi \approx 0.5$. The pion fragmentation functions, indicated by $W_\pi(x, m_x)$ are then normalized as

$$\int_0^1 dx x W_\pi(x, m_x) = f_\pi \tag{12}$$

where $x = 2E_\pi/m_x$. Approximately 1/3 of f_π is carried away by neutral pions while a fraction 2/3 goes into charged pions. Each X-particle will produce two jets with energy $m_X/2$ each.

The choice of the fragmentation function and its normalization are delicate points and deserve some additional comments: both the MLLA fragmentation functions considered here (QCD and SUSY-QCD) are still valid for $x \ll 1$, though they represent an improvement with respect to the simple approximation in eq. (1). This implies a lack of consistency in the way we normalize the fragmentation function through eq. (12) since the integral extends to a range of values of x where the fragmantation function is not accurate. Recently this problem has been treated more carefully in [7] and several new interesting results have been obtained. In [7] the HERWIG QCD event generator was used to investigate the structure of the hadronic cascade at large values of m_X. In this approach the normalization of the fragmentation function can be carried out self consistently. More interestingly however, the authors of [7] also find appreciable differences between the fragmentation functions produced by their montecarlo tecnique and the functions generally used in these calculations as well as in the present work. The differences, as could be expected, vanish for $m_X \leq 10^3$ GeV, where the MLLA approximation is known to work well. A striking difference between the montecarlo approach and the MLLA approximation is that the fragmentation functions for protons and pions (and therefore neutrinos and gamma rays) have different shapes for large values of x (while we assumed here that the shape of the two functions is the same but with a different normalization). Moreover, for $0.2 \leq x \leq 0.4$ the authors of [7] seem to obtain equal abundancies of nucleons and gamma rays, which is a very different result from the usual assumption that the gamma rays are a factor ~ 10 more abundant than nucleons in the hadronic cascade. The combination of different normalization and different shape of the fragmentation functions suggested in [7] can affect the conclusions presented in this paper and more in general the calculations of particle fluxes in top-down models of UHECR. Unfortunately, since the results in [7] are purely numerical it is not easy to envision in what direction the results presented here would change, therefore, we assume here that the fragmentation process is well represented in the MLLA approach introduced above, stressing that a detailed study of the problem would certainly be useful.

Since the electrons radiate through synchrotron emission, a model for the galactic magnetic field is also needed. We parametrize the magnetic field in the form

$$B(r,z) = B_0(r) exp(-z/z_0) \tag{13}$$

where $B_0(r) = 3(r_\odot/r)\mu G$ when the radial distance r in the disc is larger than 4 kpc and $B_0(r)$ =const for $r < 4$ kpc (e.g. [20]). The parameter z_0 is fixed at 0.5 kpc and $r_\odot = 8.5$ kpc is the distance of the sun relative to the galactic center. z is the height above the galactic disc.

According to [12] the flux of gamma rays with energy E_γ produced in the π^0 decay is given by

$$I_\gamma^{UHE}(E_\gamma) = \frac{W_\gamma(E_\gamma)}{4\pi} \int_{-1}^{1} dcos\theta |cos\theta| \int_0^{r_{max}(\theta)} dr \dot{n}_X^h(R) \tag{14}$$

where $r_{max}(\theta)$ is easily calculated to be

$$r_{max}(\theta) = r_\odot cos\theta + \sqrt{R_h^2 - r_\odot^2 sin^2\theta} \tag{15}$$

and R_h is the size of the halo. The angle θ is measured with respect to the direction of the galactic center. The gamma ray spectrum at the production is given by [12]

$$W_\gamma(E_\gamma) = \frac{4}{m_X}\int_{2E_\gamma/m_X}^{1}\frac{dx}{x}W_{\pi^0}(x,m_X) \tag{16}$$

with $W_{\pi^0}(x,m_X) = (1/3)W_\pi(x,m_X)$.

The comparison of the observed UHECR flux at $E = 5\cdot 10^{10}$ GeV with the flux of gamma rays from eqs. (14-16) at the same energy gives the normalizing value of $\dot{n}_0^h$ for each specific choice of the values of the parameters. We plot our fluxes of UHE gamma rays at the normalization point in Fig. 1.

The spectrum of UHEE is the convolution of the pion and muon spectra and is given by

$$W_e(E_e) = 12E_e^2\frac{m_\pi^2}{m_\pi^2-m_\mu^2}\frac{2}{m_X}\int_{E_e}^{m_X/2}dE_\mu\frac{1}{E_\mu^3}\left[1-\frac{E_e}{E_\mu}\right]\int_{2E_\mu/m_X}^{2r^2E_\mu/m_X}\frac{dx}{x}W_{\pi^\pm}(x,m_X), \tag{17}$$

where $r = m_\pi/m_\mu$. The spectrum of electrons produced by a single muon is peaked at $E_e \approx (2/3)E_\mu$. In the simple assumption that all electrons are produced with this peak energy the above electron spectrum becomes

$$W_e(E_e) = \frac{3}{m_X}\frac{m_\pi^2}{m_\pi^2-m_\mu^2}\int_{3E_e/m_X}^{3r^2E_e/m_X}\frac{dx}{x}W_{\pi^\pm}(x,m_X). \tag{18}$$

As pointed out in the previous section the UHEE radiate by synchrotron emission in the galactic magnetic field in the gamma ray energy range, according with eq. (5). The emissivity per unit volume in the form of gamma rays with energy E_γ at the position at distance R from the galactic center can be written as

$$q_\gamma(E_\gamma,r,z) = \dot{n}_X^h(R)W_e(E_e)\frac{E_e}{E_\gamma}\frac{dE_e}{dE_\gamma} \tag{19}$$

where E_e and E_γ are related through eq. (5) but the magnetic field is now a function of the position in the galaxy. Hence the same E_γ will correspond to different E_e in different positions in the galaxy.

Since the magnetic field is symmetric with respect to the disc while the dark matter profile is spherically symmetric, the integration over lines of sight requires the explicit integration over both θ and ϕ, so that the flux of gamma rays at the Earth, per unit time, surface, energy and solid angle is

$$I_\gamma(E_\gamma) = \frac{1}{4\pi}\int_0^{2\pi} d\phi \int_{-1}^{1} dcos\theta \; |cos\theta| \int_0^{r_{max}(\theta)} dr q_\gamma(E_\gamma, r, z), \tag{20}$$

where $r_{max}(\theta)$ is again given by eq. (15).

The total observed gamma ray flux at energy E_γ, $I_\gamma^{tot}(E_\gamma)$, is the sum of the synchrotron gamma ray flux [eq. (20)] and the primary gamma ray flux [eq. (14)].

The results of the calculations are plotted in Figs. 2 and 3, where we used $r_0 = 10$ kpc and $z_0 = 0.5$ kpc. Although the calculation has been carried out for the three sets of values of the α, β, γ parameters, the results are quite insensitive to the specific model of the halo distribution of dark matter, and the related curves would be indistiguishable. Therefore we plotted there only the case $(\alpha, \beta, \gamma) = (2, 2, 0)$ for reference. In Fig. 2 we plotted $E_\gamma^{1.75} I_\gamma^{tot}(E_\gamma)$ in order to amplify the spectral differences. The two thick lines refer to $m_X = 10^{14}$ GeV, while the two thin lines are for $m_X = 10^{13}$ GeV. The solid curves are obtained using the SUSY-QCD fragmentation function while the dashed lines are calculated with the ordinary QCD fragmentation function. For comparison we also plotted by a dash-dotted line the extragalactic diffuse gamma ray background [28]. All our fluxes are below this limit in the energy range accessible to current experiments. The points with arrows are the upper limits on the gamma ray flux from the HEGRA [21], Utah-Michigan [22], EAS-TOP [23] and CASA-MIA [24] experiments.

Clearly the stronger constraints on the gamma ray flux from the halo are imposed by the CASA-MIA and EAS-TOP experiments. In most of the cases considered in this paper the fluxes are below these limits, with the exception of the case $m_X = 10^{13}$ GeV with SUSY-QCD fragmentation function (thin solid line). Note that in this case the overproduction of gamma rays at $\sim 10^7 - 10^8$ GeV is mainly due to the primary gamma rays from π^0 decay, rather than to the synchrotron flux.

In Fig. 3 the gamma ray fluxes have been blown up in the energy range between 100 MeV and 10^4 GeV (lines labelled as before) and compared with the sensitivity of some of the present or planned gamma ray experiments in the same energy range (e.g. EGRET, GLAST, MILAGRO).

It could be particularly interesting to look at the gamma ray signal in the region above ~ 500 GeV, where the contamination due to the isotropic diffuse gamma ray background, believed to be of extragalactic origin, should be reduced due to absorption of gamma rays on the infrared background. Our calculations show an integrated flux above 500 GeV at the level of $\sim 10^{-12}$ photons $cm^{-2}s^{-1}sr^{-1}$ in our best case scenario.

There is clearly a dependence of the results on m_X, introduced by the fragmentation functions, more complicated than the simple power law adopted in section II. The difference is particularly evident on the tail of the spectra where the highest energy electrons (with energy close to $\sim m_X/2$) are probed.

We also checked that our predictions do not depend appreciably on the typical scale height z_0 of the magnetic field (eq. (13)).

A few comments about the results presented in the figures are needed: the factors 4π in eqs. (14) and (20) scale the fluxes to the unit solid angle; this is the correct procedure only for an isotropic distribution of the arrival directions of the gamma rays. Due to the anisotropic distribution of the dark matter halo and of the magnetic field of the Galaxy as seen from the sun, neither the synchrotron flux nor the primary gamma ray flux are isotropic. In fact our preliminary results of the anisotropy for the synchrotron gamma rays [27] shows a pattern of arrival directions which is quite different from the one of primary gamma rays, calculated in [12] and [11]. In this sense the fluxes per unit solid angle plotted in the figures must be intended as indicative of the 'real' fluxes, but more detailed calculations are definitely needed in this direction. For the same reason, summing up the contribution of primary and synchrotron gamma rays as done above is not self consistent for fluxes anisotropic in different ways. A peculiar finding in the anisotropy pattern could be important to discriminate the synchrotron gamma rays produced by SH particles from other background components and could improve the possibility to detect the signal discussed here.

IV. CONCLUSIONS

We calculated the flux of gamma radiation produced through synchrotron emission in the galactic magnetic field from ultra-high energy electrons generated as decay product of charged pions in the hadronic cascade coming from the decay of X-particles, when they cluster in the galactic halo in the form of SH ($m_X \sim 10^{13} - 10^{14}$ GeV) quasistable particles.

If the magnetic field in the galactic halo is $B_{halo} \sim 0.1 - 1\mu G$, UHEE with energy between 10^{17} eV and $\sim m_X/2$ very rapidly loose all their energy in the form of gamma rays mostly with energies $E_\gamma \leq 10^6 - 10^8$ GeV. The resulting diffuse gamma ray emission above 100 MeV is of the order of 10^{-8} photons $cm^{-2}s^{-1}sr^{-1}$ in the best case scenario. This result is not strongly dependent on the mass m_X of the SH particles (though some dependence is introduced due to the fragmentation functions used here) nor on the geometry of the galactic dark matter halo, but depends critically on the energy where the contribution of SH relic particles to UHECR becomes dominant (section III). The shape of the fragmentation functions at very high energy can affect the result in several ways, and an accurate procedure of extrapolation of the fragmentation functions tested in accelerator experiments up to extremely large values of m_X is needed, as stressed in [7]. In fact in [7] appreciable differences were found respect to the MLLA approximation used here, when the fragmentation functions are determined by using the HERWIG QCD event generator.

In section II we also estimated the extragalactic flux of gamma rays due to the same physical process, and found that, for typical extragalactic magnetic fields of $\sim 10^{-10} - 10^{-9}$ Gauss the extragalactic and the halo fluxes are comparable, if SH particles provide a fraction $\Omega_{CDM}h^2 = 0.2$ of the CDM and the SH particles in the halo explain the UEHCR flux (the galactic and extragalactic densities of SH particles are related through eq. (9)).

It is interesting to note that the detection of a residual gamma ray emission from the halo, after the subtraction of the contribution of pp collisions, Inverse Compton scattering, electron bremsstrahlung and of the extragalactic diffuse gamma ray background was recently claimed. This subtraction procedure is quite difficult and very model dependent; however the analysis in [25] and [26] show that the residual emission is at the level of $\sim 10^{-7}$ photons $cm^{-2}s^{-1}sr^{-1}$ above 1 GeV with a spectrum $E_\gamma^{-\alpha}$ and $\alpha \approx 1.8$. This flux, if confirmed, is larger than what is found in the present calculation with the normalization at the UHECR flux carried out at $5 \cdot 10^{10}$ GeV, but the power index $\alpha \approx 1.8$ is close to 1.75 in eq. (7). In the more realistic calculations illustrated in section II the spectrum cannot be approximated by a unique power law but in the energy region between 100 MeV and a few GeV the slope of the spectra in the log-log plot is around $1.8 - 1.9$.

The origin of the residual emission is still under debate and the possibility of an underestimate of the contribution of inverse Compton scattering is an open possibility, so that the actual residual emission (if any) could be smaller than what previously claimed. In this prospective it is interesting to study the contribution of SH particles in the halo to this emission as an open intriguing possibility requiring further investigation, though probably only next generation gamma ray detectors can shed a new light on the problem.

A particularly interesting aspect is the anisotropy of the gamma ray emission expected in this model [27]. The anisotropy is the result of both the asymmetric configuration of the magnetic field in the galaxy as seen from the Earth, and the asymmetric position of the solar system in the galaxy (this also produces some anisotropy in the arrival directions of UHECR [11–13]).

The upper limits reported in Fig. 2 are due to the HEGRA [21], Utah-Michigan [22], EASTOP [23] and CASA-MIA [24] experiments. The stronger constraints to the model of SH particles in the halo come from the CASA-MIA and EASTOP experiments: the calculated fluxes are compatible with the experimental limits with the exception of the case obtained for $m_X = 10^{13}$ GeV and the SUSY-QCD fragmentation function. In this case the exceeding limit is mainly due to the primary gamma rays from π^0 decay rather that to the synchrotron gamma rays.

We propose that it could be of particular interest to study the gamma ray emission from the halo in the energy range $E_\gamma \geq 500 - 1000$ GeV, for two reasons: a) the diffuse extragalactic gamma ray background is expected to be less pronounced in this energy range because of absorption of gamma rays in the intergalactic medium on the infrared photon background; b) the spectrum of the gamma radiation from SH relic particles is predicted to have a spectrum $E_\gamma^{-\alpha}$ with $\alpha \approx 1.7-2$, substantially flatter than the gamma ray emission from pp collisions (expected to have the same spectrum as the cosmic rays) which should dominate over other mechanisms at these high energies.

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Figure Captions

Fig. 1: Flux of UHE gamma rays from π^0 decay for the case of SH particles in the halo. The thick lines are for $m_X = 10^{14}$ GeV and the thin lines are for $m_X = 10^{13}$ GeV. The solid lines are obtained with the SUSY-QCD fragmentation function [14], while the dashed lines are for the ordinary QCD fragmentation function [19]. The fluxes are multiplied by E^3. Data points are from ref. [1].

Fig. 2: Total flux of gamma rays as sum of the synchrotron emission of UHEE in the galactic magnetic field and the contribution of the decay of neutral pions. Lines are labelled as in Fig. 1. Fluxes are multiplied by $E_\gamma^{1.75}$ to emphasize the spectral differences among the curves. Upper limits are from the HEGRA [21], Utah-Michigan [22], EASTOP [23] and CASA-MIA [24] experiments. The dash dotted line is the extragalactic diffuse gamma ray background from EGRET [28].

Fig. 3: Flux of gamma rays (multiplied by E_γ) for the same cases as in Fig. 2 but limited to the energy range 100 MeV $\leq E_\gamma \leq 10^4$ GeV. Lines are labelled as in Fig. 1. The sensitivity of the EGRET, GLAST and MILAGRO experiments are drawn.

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