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Ultra high energy cosmic rays from sequestered X bursts

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Abstract

Assuming that there is no GZK (Greisen–Zatsepin–Kuzmin) cut-off and that super-GZK cosmic rays correlate with AGN (active galactic nuclei) at cosmological distances, it is speculated that a relic superheavy particle (X) has its lifetime enhanced by sequestration in an extra dimension. This sequestration is assumed to be partially liberated by proximity of merging supermassive black holes in an AGN, temporarily but drastically reducing the lifetime, thus stimulating an X burst. Based on sequestration of the decay products of X, a speculative explanation of the observed γ/N ratio is proposed.

Keywords: GZK cut-off; AGN; Cosmic rays; Black holes; Relic particle

Ultra high energy cosmic rays (UHECR) with primary energy above the Greisen–Zatsepin–Kuzmin (GZK) energy cut-off have already been detected, a total of between 10 and 20 times. Although this statement is not universally accepted, it is believed by a majority of the cosmic-ray community and will here be assumed along with certain other speculative assumptions. The source of such UHECR is not well established but here we assume that at least some of the UHECR originate from radio galaxies, e.g. BL Lacs, at cosmological distances of more than 50 Mpc. BL Lac type sources are a subset of those radio galaxies whose relativistic jet happens to point at Earth, and so their emission is relativistically boosted. This boosting provides an enormous selection effect for detection, and so at 5 GHz radio frequency, for instance, half of all radio sources are such cases, relativistic jets pointing at Earth—and demonstrating this by a flat radio spectrum.

There have been a number of hints, that the arrival directions of some ultra high energy cosmic ray events correlate with the direction to active galactic nuclei (AGN) (e.g. [1–6]), often with active galactic nuclei at distances much farther than allowed for simple protons or neutrons due to their interaction with the cosmological microwave background (for a broad and deep review, see [7]). The problem we propose to solve here is how a particle can survive the microwave background interaction, and yet be correlated with an active galactic nucleus.

In particular, we shall investigate the possibility introduced in [8] that the longevity of a precursor superheavy particle (X), along with important properties of the decay of X, are due to sequestering in a 5th dimension. Some other issues in using superheavy progenitors for UHECRs are discussed in [9].

There may be more than one extra dimension but our mechanism is adequately illustrated by a 5-dimensional spacetime with coordinates (t, x_1, x_2, x_3, y) where the space is warped with 3-spatial metric $|g_{ij}| \sim e^{-Cy}$. The parameter C is of dimension mass and we may write $C = \alpha M_{\mathrm{string}}$ with M_{string} the string scale and α a parameter of order one to be discussed further below. All non-gravitational interactions are sequestered on a 3-brane, the real world brane, which has a thickness extending from $y = 0$ to $y = y_0$. Gravity, by contrast, is unsequestered and fills the entire 5-spacetime. By sequestering of X, its decay products, and the standard model particles at different loca-

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tions within the real world brane thickness, we shall construct a model consistent with the observations and the assumption that the UHECR sources are beyond the GZK mean free path of 50 Mpc.

In order to provide the requisite kinetic energy observed for the UHECR, the mass of X as top–down progenitor is assumed to be $M_X \sim 10^{14}$ GeV. The lifetime of X in a normal region of approximately flat spacetime is required [8] to be $\tau_X \sim 10^{24}$ s; by contrast, the typical lifetime for such a particle in particle phenomenology would be the $\sim 10^{-24}$ s time scale characteristic of strong interactions. We follow the proposal of [8] that the enormous suppression factor of $\sim 10^{-48}$ arises from sequestering of the wave function of X relative to its decay products. This is easily accomplished as the Gaussian suppression requires, for $10^{-48} \sim \exp(-110) \simeq \exp(-[10.5]^2)$, only a separation of the two wave functions respectively for X and its decay products of some ten times the characteristic length scale in the brane, typically the inverse of the string scale, for example, $\Delta y \simeq 10^{-35}$ m. Thus this separation may be as small as $(\Delta y)_{XY} \sim 10^{-34}$ m, but is correspondingly larger if the string energy scale is reduced.

We shall assume the dominant decay of X is $X \to Y$ where $Y \equiv (\bar{\mathcal{Y}}\mathcal{Y})$ is a bound state of heavy quarks $\mathcal{Y}$ bound by QCD into a color singlet hadron Y. This hadron Y exemplifies the "uhecron" discussed in [10].

Two scenarios must be considered, of which we shall rapidly discard the first:

- Scenario A: Y is absolutely stable and is itself the UHECR primary.
- Scenario B: Y decays into products including nucleons which act as the UHECR primaries.

Before discriminating between these two scenarios for Y, let us introduce the principal idea concerning the X lifetime and the concept of an "X burst". Above, we asserted that the lifetime τ_X is $\tau_X \sim 10^{+24}$ s in flat spacetime.

The sources of the UHECR primaries are assumed to be correlated with AGN in radio galaxies at distances beyond the GZK mean free path, specifically those radio sources, whose relativistic jet is pointed as Earth, often also referred to as BL Lac objects. Such AGN in BL Lacs are associated with mergers of supermassive black holes when the final merger can take place "quickly" meaning within, say, one to ten years in the observer frame at Earth.

Because the gravitational field in 4-spacetime is distorted by the proximity of the black hole merger, the 5th dimension will likewise be distorted because of the effects of warping. We shall argue that the separation $(\Delta y)_{XY}$ can be reduced thereby relative to its value in flat 4-spacetime by as much as a factor $1/\sqrt{2}$ for distances less than about ten times the Schwarzschild radii of the black holes. This then implies the X decay is suppressed by only $\sim 10^{-24}$ rather than by $\sim 10^{-48}$ and consequently the decay lifetime decreases from $\tau_X \sim 10^{+24}$ s to $\tau'_X \sim 1$ s whereupon all the X particles within such proximity of the AGN will decay in an "X burst". We shall estimate the consequent flux of UHECRs below.

First it behooves us to justify the effect of AGN warping on the X lifetime. We can make a qualitative justification, which is sufficient to illustrate the plausibility, as follows. Bearing in mind the warping factor $e^{-\alpha M_{\text{string}} y}$ in the spatial metric the $|g_{ij}|$ becomes

$$\begin{aligned} |g_{ij}| &= \left(1 - \frac{2GMc^2}{r}\right)^{-1} \exp(-\alpha M_{\text{string}} y) \\ &= (1 - r_S/r)^{-1} \exp(-\alpha M_{\text{string}} y). \qquad (1) \end{aligned}$$

Based on this expression (1) where r_S is the Schwarzschild radius consider the change from $r = 2r_S$ to $r = 10r_S$ where the unwrapped factor $(1 - r_S/r)^{-1}$ varies from 2.00 to 1.11 (it is unity at $r = \infty$) so the suggested change in $(\Delta y)_{XY}$ of $3M_{\text{string}}^{-1}$ will occur if we choose $\alpha = [\ln(2.00/1.11)]/3 = 0.20$ in the space metric g_{ij}. This is of order one and suggests such liberation of sequestration can occur near an AGN.

Because the $\mathcal{Y}$ particles are sequestered closer in the y direction to X than are any of the standard model particles $\{q, l, \nu; g, W, Z, \gamma\}$ the decay which dominates is $\mathrm{BR}(X \to Y(\bar{\mathcal{Y}}\mathcal{Y})) = 100\%$ by the mechanism espoused in [11,12].

The particle $Y^0 = (\bar{\mathcal{Y}}\mathcal{Y})$ is a bound state hadron comprised of the heavy quarks $\mathcal{Y}$. Because $\mathcal{Y}$ is sequestered away from γ the cross section for scattering on the CMB is much smaller than for normal hadrons: $\sigma(\gamma Y) \ll \sigma(\gamma N)$ and so the mean free path for ultra high energy Y with $E \sim 10^{23}$ eV through the background radiation can be several Gpc or longer. The extra dimension thus facilitates avoidance of any GZK cut-off.

At this stage, it is necessary to pursue separately the scenarios A and B.

In scenario A, Y is stable and is the UHECR primary. According to [10], there is an upper limit on the mass of such a strongly interacting primary for the AGASA super-GZK events with $E > 100$ EeV of $M_Y < 50$ GeV. At the same time, experiments at the Tevatron analysed in [13,14] would have discovered a Y particle with any mass $M_Y < 180$ GeV. Consequently scenario A is strongly disfavored by the non-observation of Y at the Tevatron.

We are therefore led strongly to prefer scenario B where there is the decay chain $X \to Y \to N$.

There is now one final sequestration effect acting on the particle Y, additional to those allowing the longevity of X and the high $\mathrm{BR}(Y \to X) \simeq 1$. This is to overcome the problem that Y decay generically leads to too high a γ/N (and ν/N) ratio; for example, in [15,16], a $(\gamma + \nu)/(\text{total})$ ratio of decay products as high as 97% is derived for a top–down progenitor (without extra dimension(s)). This has a simple physical explanation that the hadronization produces very many pions which yield photons and neutrinos. However, such a high percentage is inconsistent with the AGASA events which are believed to be caused by predominantly strongly interacting primaries, nucleons or light nuclei. Incidentally, this is an apparent problem for the Z-burst mechanism [17] since the well measured branching ratios for Z decay would naively lead to too high $\gamma/N \sim 10$.

The resolution is that Y is sequestered nearer to $\{c, b, t; g\}$ than to $\{u, d, s, \nu, l; W, Z, \gamma\}$. Note that the sequestration of Y from γ is required also for avoidance of the GZK cut-off so this relates the potentially observed violation of GZK with the observed low γ/N ratio which now can be $\gamma/N < 1$.

Let us then summarize the sequestration sequence across the real world brane from $y = 0$ to $y = y_0$ in flat 4-spacetime. Starting at one side, say, $y = 0$ (it does not matter as the two sides are equivalent) we have Y, then X, then $\{q; g\}$, and finally $\{\nu, l; w, Z, \gamma\}$ at $y = y_0$, localized at quite different y values $y = 0, y_X, y_{\mathrm{QCD}}, y_0$ across the thickness of the real world brane.

To obtain an upper limit on the UHECR flux from the X-burst mechanism, let us first assume that the X relic constitutes all the non-baryonic dark matter. As a reference galaxy with a massive black hole we conservatively adopt a galaxy such as M87, the closest nearby powerful radio galaxy, demonstrated to be able to produce high energy particles via Fermi acceleration to about 10^{21} eV [18]; similar active galactic nuclei have been observed out to redshift 6.41 [19], far beyond the most active cosmological redshift range of high galaxy merger rates. We adopt the following parameters for such an active galaxy: The black hole has $3 \times 10^9\, M_\odot$, the galaxy itself has a dark matter halo of $2 \times 10^{13}\, M_\odot$, and an outer radius of 300 kpc. Then the Schwarzschild radius of the black hole is $r_S = 3 \times 10^{-4}$ pc.

With mass $M_X = 10^{14}$ GeV this implies a mean number density $\sim 1/(\mathrm{km})^3$ throughout the Universe. The galactic mass is $\sim 3 \times 10^{70}$ GeV and so there will be $\sim 3 \times 10^{56}$ X particles per galaxy. To be conservative, we adopt the universal dark matter profile from [20]

$$\rho_{\mathrm{DM}} = \frac{\rho_{\mathrm{DM},0}}{(r/r_0)(1 + r/r_0)^2}. \tag{2}$$

Other scalings and descriptions of the inner dark matter profile [21,22] give only weakly different numerical estimates. We adopt a DM scale of $r_0 = 3$ kpc. This integrates to give the mass inside radius $x = r/r_0$

$$M_r = 4\pi r_0^3 \rho_{\mathrm{DM},0}\left(-\frac{x}{1+x} + \ln(1+x)\right). \tag{3}$$

Around the black hole there is an increase in dark matter particles, as they are swept up in the black hole from low angular momentum orbits; the low angular momentum orbits are repopulated by gravitational disturbances, and so we have a density law in this region of $r^{-7/4}$ [23–25]; this “loss cone” refilling starts at about the Bondi–Hoyle radius r_B (e.g., [21])

$$r_B = \frac{2GM_{\mathrm{BH}}}{\sigma^2} \tag{4}$$

where the black hole begins to dominate the motions and where we adopt $\sigma = 500$ km/s for the stellar and DM particle velocity dispersion. For our putative black hole this is $r_B = 100$ pc. Matching the universal dark matter density at the Bondi–Hoyle radius gives for the mass inside 10 Schwarzschild radii then

$$M(10r_S) = M_{\mathrm{DM,tot}} \frac{1}{5}\left(\frac{r_B}{r_0}\right)^2 \left(\frac{10r_S}{r_B}\right)^{5/4}. \tag{5}$$

We consider this black hole to be fed via a merger with another galaxy, which gives us an AGN, as noted above. We have checked the scaling implied by these relations using our own Galaxy, and determined that these numbers are low estimates for the DM density, so rather conservative (e.g., [21, 22]). We emphasize again, that strong effects in general relativity are expected within a few units of the innermost stable orbit, which for a maximally rotating black hole varies from just half a Schwarzschild radius for corotation, to 4.5 Schwarzschild radii at counter-rotation, and 3 Schwarzschild radii for no rotation.

The dark matter mass inside 10 Schwarzschild radii r_S is then given by a fraction of about 6×10^{-10} of all dark matter particles. So an X-burst involves the rapid sequestered decay of 1.5×10^{47} X particles in close proximity of a supermassive black hole merger.

In X particle decay, although the decay spectrum is obviously not measured a crude but adequate upper limit for the number of Y particles and their decay hadron products produced near or below 10^{11} GeV is about $\sim 10^{48}$ particles per sequestered X burst. We note that this corresponds to a degeneration of energy content by a factor of 6×10^{-3}, since we have 6 particles of 10^{11} GeV for one particle of 10^{14} GeV. We will refer to this factor as an efficiency $\epsilon_\star$ below.

To estimate the UHECR flux we assume as typical AGN distance the Hubble distance of $d_{\mathrm{AGN}} = 4.5\ \mathrm{Gpc} \simeq 1.5 \times 10^{23}$ km and one such merger per year. The spherical area at that distance is $4\pi(d_{\mathrm{AGD}})^2 = 3 \times 10^{47}\ \mathrm{km}^2$ and so the maximum flux at the Earth is seen to be

$$\sim 300/\mathrm{km}^2/\mathrm{century}. \tag{6}$$

We could use here a model for the cosmological evolution, and also a model for the luminosity function of active black holes, i.e. AGN, at high redshift (see, e.g., [26]). We note that the galaxies which are the most massive today, have the biggest black holes, and so had the highest merger rate in the past (see, e.g., [27,28]); considering all the uncertainties inherent in our estimate, our simple approach should suffice for now.

The observed flux of super-GZK events is about one per square kilometer per century but we assumed that *all* dark matter is made from X particles and if instead we make a much more reasonable assumption that just a few percent of dark matter is involved then the flux rate of UHECR becomes sufficiently close to observation to encourage us to take the X burst mechanism as a speculative but serious candidate for the new physics (see, e.g., [29] for a view what dark matter might be).

We can perform several more tests:

First, we can estimate the luminosity produced in this mechanism. We consume all the X-particles within the 10 Schwarzschild radii in our simple approximation. This consumption is at about the escape speed at that distance, which is about $c/5$

$$L_X = \frac{M(10r_S)c^2}{50r_S/c}\epsilon_\star. \tag{7}$$

This yields then

$$L_X = 4 \times 10^{49}\ \mathrm{erg/s}\frac{M_{\mathrm{BH}}}{3 \times 10^9\, M_\odot} F \tag{8}$$

with

$$F = \frac{M_{\mathrm{BH}}}{3 \times 10^9\, M_\odot}\left(\frac{3\ \mathrm{kpc}}{r_0}\right)^2 \left(\frac{\sigma}{500\ \mathrm{km/s}}\right)^{-3/2} \frac{\epsilon_\star}{6 \times 10^{-3}}. \tag{9}$$

The fundamental plane correlations of elliptical galaxies [30] show that this function $F \approx 1$ is only weakly dependent on mass of the black hole, or mass of the galaxy, with an approximate relation of $F \sim M_{\mathrm{BH}}{}^{-3/8}$.

This suggests one more time, that we overestimate the amount of dark matter contributing in X particles. If we insert for both relationships a factor of $1/100$, then we finally predict a flux contribution of 1 particle per km^2 and per century, and a corresponding luminosity in high energy cosmic rays of

$$L_X \approx 4 \times 10^{47}\ \mathrm{erg/s} \frac{M_{\mathrm{BH}}}{3 \times 10^9\ M_\odot}. \tag{10}$$

It is notoriously difficult to estimate observed flux from single events, but a very crude estimate can be gotten this way, and it suggests that the sources are emitting some fraction of the Eddington luminosity, which happens to be equal to the numbers given above in the last equation: The Eddington luminosity is that luminosity for which gravitational attraction and radiative repulsion balance for an electron/proton plasma. In our context this measure has no physical relevance except that observationally we happen to know that all well determined sources appear to obey this limit. Therefore the luminosity above derived from an entirely different argument is consistent with observations.

Second, we can also estimate the directionality: Since the high energy cosmic ray events correlate with relativistic jets pointing at us—flat spectrum radio sources are all such jets, [31]—the squeezing of space around the merger must also produce a directionality in the emitted Y particles, with similar angular opening. This directionality is almost certainly the direction of the spin of the merged black hole; that is the dominant spin in the system. This squeezing once again enhances the apparent luminosity, and so we could lower the fraction of dark matter associated with the X particles even further. Otherwise the correlation would disappear.

More correctly, the alignment of the Y decay products from X decay with the BL Lac jet axis is expected to result not from a squeezing of three normal spatial dimensions but of the additional dimension. The lifetime of X is expected to be the most shortened for decay $X \to Y$ in the axial direction as a qualitative result of the scale in the extra dimension as in Eq. (1) tracking the scale of the ergosphere in the familiar Kerr solution which the newer five-dimensional solutions [32,33] generalize. In the well known Kerr solution the ergosphere has its largest scale equatorially, and here the warping of the fifth dimension is correspondingly weakest. The concept of an anisotropic lifetime may sound unfamiliar but is not surprising for a lifetime hypersensitive to the warping factor. Our discussion is necessarily only qualitative but the beaming of the Y particles from X bursts along the BL Lac jet by this mechanism is quite plausible.

Third, we can work out the time spread: The emission is made with a time of $50 r_S/c$, which for a black hole of mass of 3×10^9 solar masses is about a week. And yet, since the estimated lifetime of activity of flat spectrum radio sources is believed to be about 10^8 years, the arrival time of the decay products of the Y particle may be spread out, and that can be understood as the time spread from the decay at various distances along the path to us, which is given by a fraction of $1/(2\gamma_Y^2)$ of the travel time from the source to us. The travel time for a photon at our adopted standard distance is of order 10^{10} years, and so the Y has to have a Lorentz factor of at least 10, or a mass of less than 10^{13} GeV. If the mass were larger, then the arrival would not correlate with an activity episode of an AGN anymore, since the spreading would be longer than the activity episode lifetime of the AGN. However, the spreading could be smaller, since we associate only a small fraction of the visible flat spectrum radio sources with the high energy particle emission. Any correlation with just a few sources, which can each supply a major fraction of the flux, suggests, that in the observer's frame the time spread is of order 1–10 years, and this would suggest that the Y has a mass of order a few 10^9 GeV. Obviously, this is a very crude estimate, since we should really be doing a convolution with cosmological evolution, and with a distribution function of AGN power levels. With good statistics of associations with flat spectrum radio sources we might be able to derive a better estimate for the mass of the Y. But this should point to the right range.

Fourth, we can obtain a limit on the lifetime of the Y particle in the observer frame: For particles that decay within a small fraction of the path to us, the resulting hadronic flux is exponentially suppressed by the interaction with the microwave background; while for Y particles whose decay time is much longer than the transit time, the rate of decay at our distance could be quite low, but this suppression is only with the inverse of the lifetime; however, this last effect could be compensated by some of the other effects, which increase the flux, such as beaming (see above). Basically, the lifetime in its own frame has to be of order 10^9 years or some factor of order at most 100 longer.

Last we wish to suggest how to test this proposal, and how to distinguish it from other suggestions to explain such a possible correlation between UHECR and AGN: There is basically one other suggestion, and that is an effect of quantum gravity could shift the threshold for the interaction between protons and neutrons, in such a way, that protons would decay, and neutrons would survive in the interaction with the microwave background (e.g., [34,35]). This would again imply a directional correlation, because the particles surviving are neutrons; however, the basic injection would be just the same as for normal radio galaxies (e.g., [18,36,37]). This implies that the overall integrated injection spectrum of cosmic rays from such sources, taking into account the dependence of maximum energy on power of the source [38], is fairly steep. Here in our model, the injection spectrum would reproduce the decay spectrum of the Y particle, and so would be presumably quite a bit flatter.

A corollary is that dark matter does have this small contribution from such X particles.

Therefore, the observational test is the injection spectrum required to explain those UHECR events, that do correlate with AGN at cosmological distances.

UHECR (>100 EeV) are exciting as signals of new physics provided certain correlations which are still uncertain become better established. Especially, one would want to obtain an improved statistical significance of the correlations of the directions of the UHECR with the directions of the radio galaxies with AGN (BL Lacs) at distances >50 Mpc (see, e.g., [4]), as first discussed in a physical context in, e.g., [1,3,36].

The Auger detector, as well as EUSO and OWL, are expected to provide higher statistics for the UHECR. The first question to answer is whether such cosmic rays exist? (Fluorescence and ground-based measurements in AGASA, Hi-Res and preliminary Auger data seem only marginally consistent.) Second question: Do the air-shower analyses confirm that primaries are all or mostly hadronic? Third question: Is there a statistically significant correlation between UHECR (assuming such exist!) and AGNs at cosmological distances?

If the answers to all three questions are positive then it does seem that dramatically new physics will have been discovered as these three facts cannot be accommodated with known particles and forces.

Extra dimensions are purely speculative at present. They just might show up at the planned colliders but they may have insufficient energy. The uniquely high energies of 100 EeV cosmic rays could be the first opportunity to detect extra dimensions in the early 21st century just as cosmic rays led to the original discoveries of important elementary particles like e^+, μ, π, K and others in the first half of the 20th century.

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