Longevity and Highest-Energy Cosmic Rays

Paul H. Frampton, Bettina Keszthelyi and Y. Jack Ng

Department of Physics and Astronomy,
University of North Carolina, Chapel Hill, NC 27599-3255

Abstract

It is proposed that the highest energy $\sim 10^{20}$eV cosmic ray primaries are protons, decay products of a long-lived progenitor which has propagated from typically $\sim 100$Mpc. Such a scenario can occur in e.g. $SU(15)$ grand unification and in some preon models, but is more generic; if true, these unusual cosmic rays provide a window into new physics.
Important discoveries in particle physics were at one time dominated by the study of cosmic rays [1]. Examples are the discovery of the positron [2], the muon [3], the pion [4], and the first strange particles including the kaon [5]. In the last several decades, most of the important discoveries have been made under the more controlled situation of accelerators. Nevertheless, the distinguished history for cosmic rays may be about to repeat, if the highest-energy cosmic rays reflect new physics.

The cosmic rays which exceed the GKZ cut-off [6] at a few times $10^{19}$ eV are of particular interest, because for protons this cut-off which is based on pion photoproduction from the cosmic microwave background (CMB) seems very well founded. The derivation is as follows: using for Boltzmann’s constant $k_B = 8.62 \times 10^{-5}$ eV/°K and taking the temperature of the CMB as 3°K gives an average photon energy $\epsilon = 8 \times 10^{-4}$ eV. In the CMB frame a collision $p(p_1) + \gamma(p_2) \rightarrow \Delta \rightarrow N\pi$ has $p_1 = (E, 0, 0, k), p_2 = (\epsilon, 0, 0, -\epsilon)$ and squared center of mass energy $s = (p_1 + p_2)^2 = m_{\pi}^2 + 2(E + k)\epsilon = m_{\Delta}^2$. For the relativistic case $E_p \simeq k$ and $E_p^{(resonance)} = (m_{\Delta}^2 - m_{\pi}^2)/4\epsilon = 2 \times 10^{20}$ eV. This is for the average energy: considering the more energetic CMB photons, the limit falls to a few $\times 10^{19}$ eV. For protons above this energy, the pion photoproduction from CMB will dominate beyond the mean free path. In the nonrelativistic case, when $E_p$ is not equal to $k$ one must keep all terms and find then $E_X + (E_X^2 - m_X^2)^{1/2} = (s_{threshold} - m_X^2)/2\epsilon$ where $X$ is the primary and $s_{threshold}$ is the appropriate squared center of mass energy. One could argue that for $E_p$ much larger than $E_p^{(GKZ)}$ there could be multiple scattering of the photoproduction type before the energy degrades to that already observed for cosmic rays. But then there should be cosmic rays of the higher energies without multiple scattering, and it remains to be seen whether these are observed.

The mean free path ($\lambda$) of protons follows from the pion photoproduction cross-section $\sigma = 200 \mu b$ (at the $\Delta(1236)$ resonance) and the density $\nu = 550$ photons/cm.$^3$ for the CMB. Thus,

$$\lambda = (200 \times 10^{-30} \text{cm}^2)^{-1} (550)^{-1} \text{cm}^3 = 9 \times 10^{24} \text{cm.} \simeq 3 \text{Mpc}. \quad (1)$$
independent of the energy provided that $E_p >> m_p$.

This distance is an order of magnitude larger than our galactic halo ($\sim 100$kpc.) but is small compared to the Local Cluster ($\sim 100$Mpc.). It would suggest that the protons would need to originate within our galaxy, and hence be directed mainly from the galactic plane. But the problem is that the maximal galactic fields are $\sim 3 \times 10^{-6}$G with coherence length $L \sim 300$pc. so a proton can typically be accelerated only to an energy:

$$eBL \sim \left(\frac{4\pi}{137}\right)^{1/2} (3 \times 10^{-6}G)(300\text{pc.}) \simeq 10^{15}eV$$

several orders of magnitude too small. A further problem is that such high energy $\sim 10^{20}$eV. protons are hardly deflected by the interstellar magnetic fields and hence should have a direction identifiable with some source. To see this, note that for $E = 10^{11}$GeV, a proton of charge $1.6 \times 10^{-19}$ Coulombs in a magnetic field $3 \times 10^{-6}$ gauss has a minimum radius of curvature of 30kpc. comparable to the radius of the galaxy. In fact, if anything, the eight $> 10^{20}$eV. cosmic ray events in hand are oriented along the extragalactic plane and have no known correlation with any identifiable sources. In short, these events are irresistible to a theorist.

These eight events are from the AGASA [7], Fly’s Eye [8], Haverah Park [9], and Yukutsk [10] collaborations. The international Auger project [11] would be able to find hundreds of such events if it is constructed and will likely shed light on the angular distribution and on the presence of even higher energy primaries. The existing events have shower properties and chemical composition consistent with proton primaries.

Explanations offered for these extraordinary cosmic rays have included protons originated from nearby (but invisible otherwise) topological defects/monopoliun [12], and magnetic monopoles [13] that in the interstellar magnetic field can pick up an amount of kinetic energy $(q_M/e) \sim 10^3$ times higher than protons.

We investigate a different possibility. We hypothesize a particle $X$ with mass $M_X$ and lifetime $\tau_X$, and whose cross-section with the CMB photons is below $6\mu$b so that the $\lambda$ in Eq.(1) is above 100Mpc. The particle $X$ can be electrically neutral or charged. Suppose $X$
is like a heavy quarkonium in QCD; then the linear size scales as $M^{-1} \ln M$ and we expect a 500TeV pseudoscalar to be several orders of magnitude smaller than a proton and hence that its cross-section $\sigma(\gamma X)$, which is $\sim (\text{length})^2$ is correspondingly numerous orders of magnitude smaller than $\sigma(\gamma p) = 200\mu b$. We assume that $X$ which obtained its kinetic energy as the decay product of a GUT particle $G$ approximately at rest decays into a proton within a few Mpc. of the Earth and that this proton is the cosmic ray primary.

Let us consider $E_X = 2 \times 10^{20}$ eV. and let $M_X$ be in GeV, $\tau_X$ in seconds and the distance $d$ be in Mpc. We assume $X$ is highly relativistic $E_X >> M_X$. Then

$$\frac{\tau_X (\text{sec})}{M_X (\text{GeV})} = 500d (\text{Mpc})$$

For a first example, take the neutron with $\tau_X \simeq 1000$ and $M_X \simeq 1$; this will travel 2Mpc. It is an amusing coincidence that this is close to the proton mean free path, but it means that the neutron does not travel far enough to be the source we seek.

Let us revert to particle theory and ask for a neutral $X$ which will decay very slowly into ordinary quarks. Suppose, as an example, that there is a pseudoscalar $X^{\alpha\beta}$ of color $X_{\gamma\delta}$ coupling to four quarks by:

$$\frac{1}{M_G^3} X^{\alpha\beta} q_{\alpha} \gamma^5 q_{\gamma} \bar{q}_{\beta} q_{\delta}$$

with a suppression appropriate to a dimension-7 operator, according to some GUT scale defect with mass $M_G \simeq 2 \times 10^{11}$ GeV whose decay provides the kinetic energy $E_X >> M_X$. Because $X$ is pseudoscalar, lower-dimension operators with gluons, e.g. $X G^{\mu\nu} \tilde{G}_{\mu\nu}$ will be further suppressed.

The lifetime of $X$ may be roughly estimated as:

$$\tau_X \sim (10^{-23} \text{sec.}) \left( \frac{M_X}{2 \times 10^{11} \text{GeV}} \right)^{-6}$$

To fix parameters, let us take a distance scale $d = 100 \text{Mpc}$. This fixes $M_X \simeq 500\text{TeV}$ and $\tau_X \sim 3 \times 10^{10} \text{sec.} \sim 1000 \text{ years.}$
Is this picture natural from the point of view of the particle theory? We need two scales: $M_G \simeq 2 \times 10^{11} GeV$, $M_X \simeq 500 TeV$ and a pseudoscalar $X$ which is a 27 of color, coupling to normal matter predominantly by $d = 7$ operators.

A specific example [14] occurs in $SU(15)$ where the GUT scale can be $M_G = 2 \times 10^{11} GeV$ and the scale $M_X$ is identifiable with the scale called $M_A$ at which $SU(12)_q$ breaks to $SU(6)_L \times SU(6)_R$. For $X$ one can see by studying [14] that the 14,175 dimensional $SU(15)$ Higgs irreducible representation contains an appropriate candidate.

Can the ancestor G particles at the GUT scale be uniformly distributed without over-closing the universe? A crude estimate follows:

Take a spherical shell of radius $R$ and thickness $\Delta R$, let the Earth radius be $R_\oplus$. For simplicity assume the lifetime for G is the present age of the universe $A = 10^{10} y$. The event rate in question is $\sim 1/km^2/y$ at the Earth’s surface so we have for $\nu_G/cm^3$ the number density of G particles:

$$1 \simeq \frac{1}{A} \left[ \nu_G \frac{4\pi}{3} (6R^2 \Delta R) \right] \frac{\pi R^2_\oplus}{4\pi R^2} \frac{1}{4\pi R^2_\oplus}$$

Putting $\Delta R = 2 Mpc$, $A = 10^{10} y$, and $M_G = 2 \times 10^{11} GeV = 2 \times 10^{-13} g$ gives the mass density $\rho_G$:

$$\rho_G = \nu_G M_G \sim 10^{-37} g/cm^3$$

corresponding to a contribution $\Omega_G < 10^{-8}$ to the closure density. If the distribution of G is not uniform but clustered in e.g. AGNs the $\Omega_G$ will presumably become even smaller. If we consider much larger $d >> 100 Mpc$, the red-shift would have to be taken into account in such calculations. In all such cases, the required density of GUT defects G is consistent in the sense that it contributes negligibly to the cosmic energy density.

This first example was merely an existence proof. The most unsatisfactory feature is surely the color non-singlet nature of $X$. It is difficult to believe such a colored state can propagate freely even in intergalactic space because of color confinement. A simple modification which avoids this difficulty is to consider two such $X$ states: $X'$ and $X''$, both
e.g. color 27-plets but non-identical. The bound state \( (X'\bar{X}'') = X \) can then be color singlet, stable with respect to \( X' - \bar{X}'' \) annihilation and unstable only by virtue of the decay of its constituents.

Three key properties of the \( X \) particle in our scenario are (1) long lifetime, \( \sim 1000\text{y} \) if dimension-7 operator(s) mediate decay of \( X \) to quarks, (2) small cross-section, below 6\( \mu \text{b.} \), with CMB photons, and (3) significant branching ratio for decay to proton(s).

What other models can exemplify this scenario? One other example we have found is based on a slight modification of the sark model \[15, 16\]. The neutral sark baryon, or ”nark”, discussed in \[16\] as a candidate for dark matter merely needs to be slightly unstable, rather than completely stable, to play the role of our \( X \) particle. Firstly, the nark satisfies property (2) because of scaling arguments (its mass is taken to be \( \sim 100\text{GeV} \)) similar to those used above. If there is a unified theory of sarks, one expects sark number to be violated and depending sensitively on the mass scale of unification this could give a nark lifetime in the desired range, property (1), as well as a sufficiently high branching ratio to protons, property (3), but without an explicit unified theory this is speculation. More work on this idea is warranted.

Properties (2) and (3) are, in general, not unexpected: the most constraining requirement is property (1). If there exists a model in which such longevity of \( X \) occurs naturally it would be a compelling candidate to be a correct description.

This work was supported in part by the U. S. Department of Energy under Grant No. DE-FG05-85ER-40219.
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