Relic Neutrinos and Z-Resonance Mechanism for Highest-Energy Cosmic Rays

James L. Crooks, James O. Dunn and Paul H. Frampton

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

Abstract

The origin of the highest-energy cosmic rays remains elusive. The decay of a superheavy particle (X) into an ultra-energetic neutrino which scatters from a relic (anti-)neutrino at the Z-resonance has attractive features. Given the necessary X mass of $10^{14}$ to $10^{15}$ GeV, the required lifetime, $10^{15}$ to $10^{16}$ y, renders model-building a serious challenge but three logical possibilities are considered: (i) X is a Higgs scalar in $SU(15)$ belonging to high-rank representation, leading to power-enhanced lifetime; (ii) a global X quantum number has exponentially-suppressed symmetry-breaking by instantons; and (iii) with additional space dimension(s) localisation of X within the real-world brane leads to gaussian decay suppression, the most efficient of the suppression mechanisms considered.
The confluence of cosmology and particle phenomenology benefits both disciplines and can lead to important new insights.

For protons propagating through the cosmological background radiation there is an energy cut-off, as discussed in e.g. [1], well-known as the GKZ effect [2,3], at an energy of $E \sim 5 \times 10^{19}$ eV. Above this energy, the photoproduction of pions at the 3-3 resonance provides an energy attenuation that prohibits travel over a distance greater than $\sim 50$ Mpc.

Nevertheless, air showers initiated by a proton (or photon) with energies above the GKZ bound have been observed [4], and this fact needs explanation.

One possibility is that the origin involves the decay of a superheavy particle as in [1] (for related earlier works, see e.g. [5,6]) but that the decay now produces a high energy neutrino which scatters from a relic background neutrino at the $Z$ pole and produces the primary. This $Z$-burst scenario was suggested in [7] and further analysed in [8,9].

The kinematics of the neutrino-neutrino collision at the $Z$ pole requires an energy $E_{\text{resonance}} = M(Z)^2/(2M(\nu))$ and taking $M(\nu) = 0.07$ eV as suggested by the SuperKamiokande data gives $M_{\text{resonance}} \simeq 10^{23}$ eV, just as needed to explain the data. This is the most attractive feature of the model.

We first estimate the mass and lifetime of the superheavy particle needed to fit the data. This requires two relationships derived in [9]. Namely the flux of cosmic rays beyond the GKZ cut-off is estimated as:

$$\Phi_{CR} = \frac{C_1}{(4\pi sr)km^2(100y)} \times \left( \frac{N}{10} \right) \left( \frac{\eta}{0.14} \right) \left( \frac{\Omega_X}{0.2} \right) \left( \frac{h}{0.65} \right)^2 \times \left( \frac{B_{\nu} 10^7 t_0}{\tau_X} \right) \left( \frac{0.07 eV}{M(\nu)} \right)^{3/2} \left( \frac{10^{14} GeV}{M(X)} \right)^{5/2} \tag{1}$$

and

$$\frac{\tau_X}{t_0} B_{\nu}^{-1} > C_2 \times 10^5 \left( \frac{\Omega_X}{0.2} \right) \left( \frac{h}{0.65} \right)^2 \left( \frac{10^{14} GeV}{M(X)} \right)^{3/4} \tag{2}$$

For the numerical dimensionless coefficients we find the values $C_1 = 0.33$ and $C_2 = 12.8$ which we use in the following analysis. The notation is: $N$ is the number of protons and
photons per annihilation event; \( \eta \) is the relic neutrino density relative to the present photon number density \( \eta = (n_{\nu, \text{relic}}/n_{\gamma,0}) \); \( \Omega_X \) is the contribution of \( X \) particles to the energy density, relative to the critical density; \( h \) is the Hubble constant in units of \( 100\text{km/s/Mpc} \); \( B_\nu \) is the branching ratio of \( X \) into neutrinos; \( t_0 \) is the age of the universe; \( \tau_X \) is the lifetime of \( X \); \( M(\nu) \) is the neutrino mass; and \( M(X) \) is the mass of \( X \).

Assuming central values of all other parameters we plot the allowed region of \( M(X) \) and \( \tau_X \) in Figure 1; variations in \( N, \eta, \Omega_X, h, B_\nu, M(\nu) \) can extend the allowed region but here we need only the order of magnitude estimate.

The value of \( M(X) \) must certainly exceed \( 2E_{\text{resonance}} \) so that a two body decay can lead to a neutrino acquiring enough energy. Higher energies can be red-shifted down to \( E_{\text{resonance}} \) if the progenitor \( X \) particle is at a red shift \( z > 0 \).

The resultant spectrum will cut-off at \( M(X)/2 \) and will be expected to provide a two-component type of overall spectrum, with a dip around \( E \sim E_{\text{GKZ}} \) as can be seen in the data [4].

Since \( Z \) decay gives rise to approximately 10 times as many photons as nucleons the model predicts a concomitant number of high-energy photons as cosmic-ray primaries. Because the data is sparse, it is not yet possible to discriminate on this basis, as discussed in [10]; this is an important prediction of the Z-burst scenario.

From the above analysis we conclude that the required particle properties \( M(X) \) and \( \tau_X \) for the hypothetical state \( X \) are well defined in order of magnitude. Namely, the mass \( M(X) \) should lie between \( 10^{14} \) and \( 10^{15} \) GeV and the lifetime \( \tau(X) \) should lie between \( 10^{16} \) and \( 10^{17} \) years.

The remainder of the paper will discuss three possible microscopic theories or, better, scenarios for this combination of \( M(X) \) and \( \tau(X) \). We present these three scenarios in what we regard as their increasing appeal, from (i) to (iii).
(i) **Power suppression.**

The expectation for a particle of this mass is that, unless it is absolutely stable due to some exact conservation law, it will decay exceedingly quickly with a lifetime expected to be $\tau \leq 10^{-24}$ seconds. Since the required lifetime is larger by some 46 or so orders of magnitude, the longevity is the principal difficulty, as emphasized in [1].

One viewpoint is that this extraordinary suppression of the decay is an argument against the model, as is the problem, already mentioned, of super-high-energy photons concomitant with the protons.

Let us here take the viewpoint, as discussed in [10] that the photons are a prediction of the model, to be tested in future experiments, rather than a fatal flaw. The data on HECR is probably too sparse to reach any stronger conclusion.

Therefore the only remaining question is longevity.

The first scenario (i) is that considered (in a different model) in [1]. We assume the particle X is a boson and posit a coupling

$$\frac{g}{M_p} X^{\alpha_1 \alpha_2 \ldots \alpha_n} (\overline{\psi}^{\beta_1} \psi_{\alpha_1}) (\overline{\psi}^{\beta_2} \psi_{\alpha_2}) \ldots \ldots \ldots (\overline{\psi}^{\beta_n} \psi_{\alpha_n})$$

where the power is $p = 3(n - 1)/2$. Let us assume that such a coupling is gravity-induced and that $M$ is the reduced Planck mass $M \sim M(Pl) \simeq 10^{18} GeV$. Then one expects the lifetime $\tau(X)$ to be of the order of magnitude

$$\tau(X) \sim (10^{-24} sec.) \times \left( \frac{M(X)}{M(Pl)} \right)^{2p}$$

in which the mass ratio is $\frac{M(X)}{M(Pl)} \simeq 10^{-3} - 10^{-4}$. To arrive at a suppression of $10^{-46}$ thus requires $2p \sim 12 - 15$ and $n \sim 5 - 6$. Thus the X field must have a high tensorial rank. If this is too much for the reader, skip to scenario (ii).

In [10] the case $n = 2$ was considered. In the spontaneous breaking of $SU(15)$ theory such a tensor appears "naturally" in the Higgs sector. There is no apparent need for such a high rank as $n = 5$ or 6, but equally no reason for their absence. The dimensions of such scalar representations in $SU(15)$ are astronomical - even for $n=2$ the dimension is 14,175 while for $n=5$ and 6 this becomes respectively 125,846,784 and 1,367,127,216.
It is difficult to believe that such power suppression could be responsible for the longevity. It is a logical possibility which appears highly contrived. Thus exponential or gaussian suppression is more appealing.

(ii) **Exponential suppression.**

Let us assume that the superheavy particle $X$ carries a conserved quantum number $Q_X$ (analogous to baryon number, $B$) and that in perturbation theory the quantum number is exactly conserved. If there is no open channel which conserves $Q_X$ then the state will be absolutely stable.

In the case of $B$ in the standard model, it was first shown in 1976 by ’t Hooft [13,14] that nonperturbative instanton effects violate conservation and lead to decay of otherwise stable states such as the proton. The resultant rate is typically exponentially suppressed by an exponential of the form $\exp(-\text{constant}/g^2)$ where $g$ is the gauge coupling constant. Many other examples of such suppression are covered in [13].

Thus, one scenario is that $Q_X$ generates a symmetry of the lagrangian but $X$ decays with exponential suppression due to instanton effects. We mention this only for completeness - any quantitative estimation would require many hypotheses.

(iii) **Gaussian suppression.**

This scenario which is, in our opinion, the most appealing involves the assumption of at least one extra spatial dimension. We will take five space-time dimensions, four space and one time.

Let the coordinates be $(x_0, x, y)$ with $y$ as the hypothetical extra dimension on which we now focus.

It used to be thought, up to a decade ago, that any such $y$ must be compactified at or beyond the GUT scale of $(10^{16} \text{GeV})^{-1} \sim 10^{-32} \text{ m}$ (recall $1(\text{GeV})^{-1} \sim 2 \times 10^{16} \text{ m}$). In 1990, Antoniadis [16] was the first to entertain very much larger compactification scales $\sim (1 \text{ TeV})^{-1} \sim 10^{-19} \text{ m}$. In 1998 it was pointed out [17, 20] that, although the strong
and electroweak interactions of the quarks and leptons need be confined to a region of \( y \) not exceeding \( 10^{-19} \text{ m} \) (the real-world brane on which we live), the gravitational interaction could be decompactified even out to \( 1 \text{ mm} = 10^{-3} \text{ m} \) without contradicting experimental data, offering the possibility of detecting such additional dimensions by deviation from Newton’s Law of Gravity at millimeter scales.

Models in which the fifth dimension contains a real-world brane and a suitably separated Planck brane which delimits gravitational propagation have been discussed in \cite{21,22}. Such models are of interest mainly because they suggest how to incorporate gravity in the conformality approach \cite{23–28} which \textit{ab initio} describes a flat (gravitationless) space-time.

Let us assume, therefore, that the standard model states are all confined within a real-world brane with a thickness of order \( 10^{-19} \text{ m} \) in the \( y \) direction. Following \cite{29} (see also \cite{30} and, for the many fold universe, \cite{31}) a scalar field \( \Phi(x_\mu, y) \) which has a \( \Phi \) domain wall in the \( y \) dimension. In the vicinity of the wall centered by convention at \( y = 0 \), and with the normalizations of \cite{29} the field has the value

\[
\Phi(y) = 2\mu^2 y
\]  

First consider chiral fermions (after all, \( X \) could be a fermion but we will consider the boson possibility later). In this case we write the five-dimensional action

\[
S = \int d^4xdy \bar{\Psi}_i[i\gamma_\mu \partial/\partial x_\mu + \Phi(y) - m_i]\Psi_i + ...
\]  

The fermion \( \Psi_i \) is now localised at \( y = m_i/(2\mu^2) \). If the Higgs \( H(y) \) is unlocalised inside the domain wall then the resulting coupling of \( \Psi_i \) to \( \Psi_j \) and \( H \) has a gaussian suppression

\[
ex^C(m_i - m_j)^2/\mu^2)
\]

where \( C \) is a coefficient of order unity. This is the gaussian overlap of the gaussian tails of the two wave functions. The thickness of the real-world brane is \( \tau \sim (\mu)^{-1} \) while the separation of the two fermion wave functions is \( \sigma \sim (\Delta y)_{ij} \). To obtain the required suppression of \( \sim 10^{-46} \) we need \( \tau/\sigma \sim 10 \). For example, if \( \tau \sim 10^{-19} \text{ m} \), one needs \( \sigma \sim 10^{-20} \text{ m} \). Clearly
only the ratio $\tau/\sigma$ matters, but need not be a large number, in order to obtain the necessary suppression.

It is worth remarking that this gaussian suppression of Yukawa couplings by localization in the fifth dimension has a long historical counterpart in the localization of states on orbifold singularities starting with [32–34] in 1987 and subsequent derivative literature [35–40].

The superheavy particle $X$ may not be a fermion but a boson, e.g. the Higgs scalar considered in scenario (i) above. Fortunately we can easily extend the localization argument of [29] to the case of a boson and obtain a similar result for the gaussian suppression of the decay amplitude and consequent longevity. We replace Eq.(4) by the following:

$$S = \int d^4xdy\phi_1^\dagger[\Box - m_S^2 + \Phi(y)^2]\phi_i + ....$$

(6)

and, analagously to the fermion $\Psi$, the boson $\phi$ is localized around $y = m_S/2\mu^2$ when $\Phi$ again has a domain wall centered at $y = 0$. Identifying $\phi$ with $X$ then provides the required longevity by the same mechanism. It would be amusing if the highest-energy cosmic rays provided the first evidence for an extra spatial dimension!

To summarize the Z-burst mechanism for the highest energy cosmic rays, it has two positive features:

1) The resonant energy derived from the Z mass and the SuperKamiokande neutrino mass is numerically close to the required energy.

2) The spectrum is predicted to have the two-component shape suggested by the present data.

On the other hand, there are also two apparently negative features:

3) The concomitant high-energy photons are not confirmed by present data. Better data will confirm or refute this important prediction.

4) The longevity of the superheavy particle is such a challenge to microscopic model-building that it may render the model less credible.

It is point (4) which we have attempted to ameliorate in the present article.
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Figure 1.

Allowed region of $M(X) - \tau_X$ from Eq.(1) and Eq.(2) of the text. In the Figure $a_X = \tau_X(t_0/10^7)^{-1}$ where $t_0$ is the age of the universe and $b_X = M(X)/(10^{14} GeV)$. Variations in $N, \eta, \Omega_X, h, B, M(\nu)$ can extend the allowed region but we use only such order of magnitude estimates.