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NEUTRINOS AND ORIGIN OF ULTRAHIGH ENERGY COSMIC RAYS

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Ultra High Energy Cosmic Ray (UHECR) particles with energies exceeding 10^{20} eV have been detected. The sources as well as the physical mechanism(s) responsible for endowing particles with such enormous energies are unknown. The existence of these extremely energetic particles is difficult to explain within the standard scenario in which charged particles are accelerated in powerful astrophysical sources and their interactions are governed by the Standard Model of particle physics. Here, after a brief review of the basic problems associated with the question of UHECR, we summarize some of the proposed ideas in the literature regarding the possible role of neutrinos in solving some of the problems associated with the question of UHECR origin. Two possible scenarios and constraints on those from UHECR are examined: The so-called "Z-burst" scenario involving massive neutrinos in the sub-eV mass range, and the scenario involving possible new (almost) strong interaction of neutrinos attributed to possible new fundamental physics (such as extra dimensions) at the highest energies of interest. The highest energy end of the cosmic ray spectrum can thus be used as a probe of possible new fundamental physics beyond Standard Model.

Key Words: Ultra High Energy Cosmic Rays; GZK Cut Off; Z Burst; Strong Interation of Neutrinos; Constraints on UHE Cosmic Rays; AGASA; HIRes

1 Introduction

The origin of the observed Ultrahigh Energy Cosmic Rays (UHECR) — cosmic ray particles with energy $E > 10^{18}\,\mathrm{eV} \equiv 1\,\mathrm{EeV}$ — is one of the major unsolved problems in contemporary astrophysics[1] [2]. Several (currently a world total of ~ 20) cosmic ray events with estimated energy in excess of 100 EeV have been detected; see, e.g., ref.[3] for a review and references to various experiments. The existence of these extremely high energy cosmic ray particles poses a serious challenge for conventional theories of origin of cosmic rays based on acceleration of charged particles in powerful astrophysical objects.

There are strong experimental indications that UHECR particles above $\sim 10\,\mathrm{EeV}$ are mainly protons. However, protons of these energies cannot be confined within the Galactic disk because their Larmor radius in the few microgauss Galactic magnetic field would be larger than the thickness of the Galactic disk. Also, there is no significant Galactic-plane enhancement in the arrival direction distribution of UHECR above $\sim 10\,\mathrm{EeV}$. These considerations imply that, within the context of the standard acceleration scenario, the sources of the UHECR particles above ~ 10 EeV must be extragalactic. There are not many obviously powerful astrophysical sources in our cosmological neighbourhood that may be able to accelerate particles to the highest observed UHECR energies. On the other hand, considering energy loss of the particles during their propagation from distant extragalactic sources to Earth, the sources are required to be able to accelerate particles to energies $\gtrsim 1000\,\mathrm{EeV} \equiv 1\,\mathrm{ZeV}$ at their sources in order to explain the observed $> 100\,\mathrm{EeV}$ events. It is in general extremely difficult to accelerate particles to such high energies even in the most powerful known astrophysical objects such as radio galaxies, active galactic nuclei or Gamma Ray Bursts by means of the standard acceleration mechanisms. Even if some of these objects are able to accelerate particles to the requisite energies, the paucity of these objects in our cosmological neighbourhood and their spatial distribution are not easy to reconcile with the observed large-scale isotropy and at the same time with the claimed small-scale anisotropy (clustering)[4] of the arrival directions of the UHECR particles, unless we are located in a region of the Universe permeated by rather special configuration and strength of magnetic field which could bend the trajectories of the charged particles from a few sources sufficiently so as to isotropize the arrival directions of the particles at Earth.

In this article we discuss how neutrinos, especially if some neutrino species have a small mass in the sub-eV to eV range, may play a role in providing solutions to some of the problems of UHECR origin. In turn, it may be possible to *determine* or at least have a handle on the absolute mass of neutrinos from accurate measurements of the UHECR spectrum. Neutrinos may also have a bearing on the UHECR problem if they have new interactions due to possible new physics beyond Standard Model at the ultrahigh energies of interest.

There are a large number of recent reviews and monographs dealing with the question of origin of UHECR; see, for example, refs.[5-8]. We urge the reader to consult these reviews for details and references to the original literature.

This article is organized as follows: In the following section, we briefly describe the main problems associated with the question of origin of UHECR. In section 3 we discuss the so-called "Z-burst" scenario[9] of the origin of UHECR, that involves small mass neutrinos, and the constraints on the scenario. Section 4 discusses the scenario involving possible new strong interactions of neutrinos allowed by some possible kinds of new physics beyond Standard Model at the relevant high energies involved. A brief summary and the main conclusions are presented in section 5.

2 The Problems of Origin of UHECR

The Observed UHECR Spectrum

The energies and nature of the primary UHECR particles are inferred from the properties of the extensive air showers (EAS) of secondary particles initiated by the individual primary UHECR particles in the Earth's atmosphere. The electrons and muons in these EASs can be detected on the ground with an array of detectors such as water Cherenkov detectors or scintillation detectors, and the energy and the direction of the primary particle that initiated the shower can be inferred from sampling of the shower particles on the ground. Currently the largest operating ground array of detectors for detecting UHECR is the Akeno Giant Air Shower Array (AGASA) near Tokyo, Japan, which covers an area of roughly $100\,\mathrm{km}^2$ with about 100 scintillation detectors[10] mutually separated by about 1 km. The ground array technique allows one to measure a lateral cross section of the shower profile. The energy of the shower-initiating primary particle is estimated by appropriately parameterizing it in terms a measurable parameter; traditionally this parameter is taken to be the particle density at 600 m from the shower core, which is generally found to be quite insensitive to the primary composition and the interaction model used to simulate EAS.

An alternative technique of detecting UHECR EASs is to detect the secondary photons induced by the EAS charged particles in the atmosphere. Currently, the largest UHECR detector that employs this method is the HiRes experiment[11] which detects the fluorescence light from the nitrogen in the atmosphere excited by the charged particles in the EAS. This method allows the measurement of the longitudinal development of the shower in the atmosphere, and the energy of the shower-initiating primary is inferred from the total fluorescence yield.

The information on the chemical composition of the primary UHECR particles is mainly provided by the muon content of the shower in the case of ground arrays such as AGASA. For optical observation of EASs, such as in the fluorescence technique employed by HiRes, the primary composition is inferred from measurement of $X_{\max}$ (measured in $\mathrm{g\,cm}^{-2}$), the atmospheric column depth at which the number of charged particles in a shower reaches a maximum. In general, for a given primary energy, a heavier nucleus produces EAS with a higher muon content and a shower maximum higher up in the atmosphere on average compared to those for a proton-initiated shower. The latter property can be understood by viewing a nucleus as a collection of independent nucleons whose interaction probabilities add, leading to a faster development of the shower on average. The higher muon content in a heavy nucleus shower is due to the fact that, because the shower develops relatively higher up in the atmosphere where the atmosphere is less dense, it is relatively easier for the charged pions in a heavy nucleus shower to decay to muons before interacting with the medium. Photon induced EASs in general have even less muon content than proton induced showers.

It should be mentioned, however, that because of large fluctuations around average behaviour, neither the muon content nor $X_{\max}$ method allows determination of the primary composition on individual shower-by-shower basis; rather the composition must be determined only statistically based on large number of events. The current data are generally consistent with UHECR above $\sim$ 10EeV being mainly protons, while below that energy heavier nuclei seem to dominate. However, above $\sim$ 100EeV, the composition is somewhat uncertain because of the rather small number of events detected so far; although the data are consistent with proton primaries, possibility of photon primaries predicted in some scenarios (see below) cannot be ruled out at present.

The measured UHECR spectra obtained by two of the largest UHECR detectors currently in operation, namely, AGASA[10] and HiRes[11] are shown in Fig.1.

It is apparent that the spectra measured by the two experiments are rather different: The HiRes data are systematically below AGASA data. More importantly, the HiRes-1 data seem to indicate a sharp fall-off of the spectrum beginning at just below $\sim$ 100EeV resembling what has come to be known[12] as the "Greisen-Zatsepin-Kuzmin (GZK) cutoff" (see below), whereas the AGASA data show no such cutoff. In fact, the AGASA data seem to hint to a spectrum above 100 EeV that is significantly harder than the one below it, which may be interpreted as signifying the emergence of a new component of UHECR above 100 EeV presumably of different origin than the one below it.

The origin of the difference between the spectrum measured by the two experiments is not clear at the present time. There have been suggestions that the differences may be due to a currently ill-understood relative systematic difference between the energy estimates of individual showers by the two completely different methods employed in the two experiments. It has, however, been claimed[13], using numerical simulation of a large number of input source spectra and including the stochastic nature of the photo-pion production interaction of the protons with the microwave background photons at the relevant energies — the main interaction process responsible for the reprocessing of the spectrum during the propagation of the energetic protons from their extragalactic source to Earth (see below) — that the two data sets are within about 2σ of one another when the simulation results are normalized to the number of events seen above $\sim$ 10EeV by the two experiments. The analysis of ref.[13] also shows that a $\sim$15% systematic energy correction in the two experiments (downward for AGASA and upward for HiRes), which are within the reported uncertainties in the energy estimations in both experiments, makes the agreement between the results of the two experiments improve considerably. Similar conclusions have also been obtained in ref.[14].

The above discussions go to show that because of the relatively small number of events above a few tens of EeV detected so far by the currently operating individual experiments, the spectra obtained from the number of detected events within given energy bins in both experiments are still dominated by fluctuations, and only large statistics experiments will be able to give a reliable measurement of the spectrum in the crucial energy region above a few tens of EeV. It may be mentioned here that the flux of UHECR at $\gtrsim$ 100EeV is $\lesssim$ 1particle/km^2/century which exemplifies the difficulty in detecting these particles and necessitates the construction of ground-based detectors with large area coverage such as the Auger[15] (which is already under construction) and the proposed space-based detectors such as EUSO[16] and OWL/AIRWATCH[17] which are expected to increase the number of events above a few tens of EeV by 2 orders of magnitude compared to that presently available. In this context, it is interesting to note that the Auger experiment, in particular, is designed to measure the individual energies of a few percent of the total number of detected events by both ground array method as well as nitrogen fluorescence method, and is thus expected to resolve the issue of the relative systematic difference in the energy estimates of individual events by the AGASA and HiRes experiments mentioned above.

The Problem of Producing ZeV Energy Particles

The standard scenario of producing high energy cosmic ray particles involves the "bottom–up" process of accelerating charged particles in suitable astrophysical environments. Currently, the standard theory of cosmic ray acceleration is the so-called "Diffusive Shock Acceleration Mechanism" (DSAM) in which particles gain energy each time they cross a moving shock front. Each particle is accelerated through a gradual process as it repeatedly crosses and recrosses a moving shock front, the particle being confined within the acceleration region by a magnetic field. This is a variant of a mechanism first proposed by Fermi[18] in 1949. Here we will not discuss the DSAM

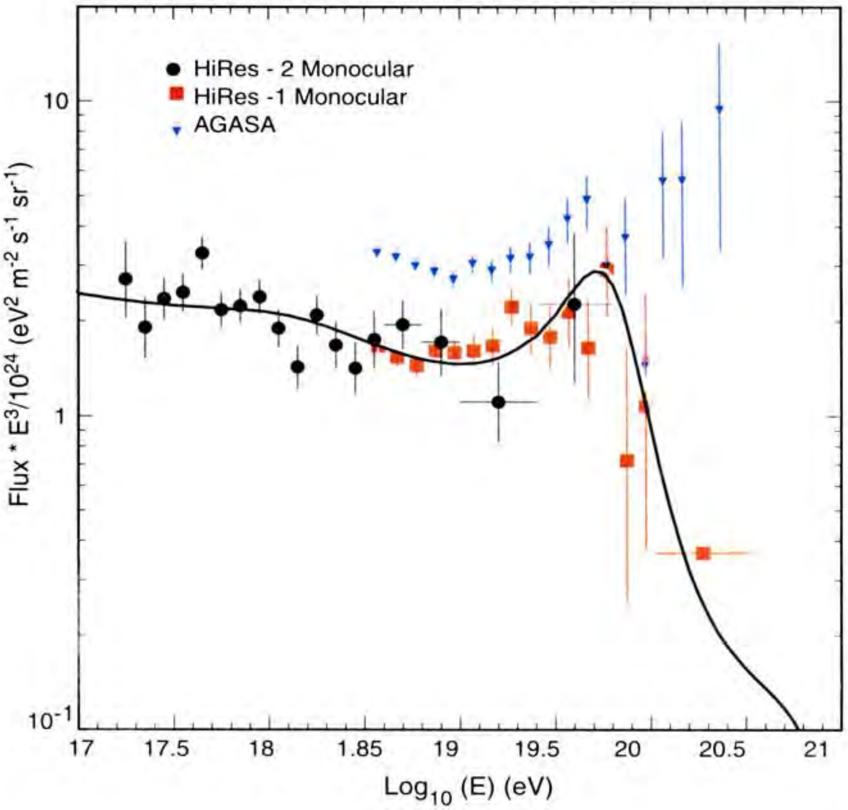

Fig. 1 The UHECR spectrum as measured by the HiRes[11] and AGASA[10] detectors. Also shown is a fit to the HiRes data of a superposition of a Galactic and an extragalactic source components. (Taken from ref.[11]).

but rather refer the reader to reviews; see, e.g., the reviews in ref.[19]. However, as first pointed out by Hillas[20], irrespective of any specific acceleration mechanism, a general estimate of the maximum energy achievable in any gradual acceleration mechanism can be obtained from the simple requirement that the size ("diameter") R of the accelerator be larger than the diameter $\sim 2r_g$ of the orbit of the particle, where $r_g \simeq E/(ZeB)$ is the gyroradius of the particle of charge Ze and energy E in the magnetic field B. This same requirement applies to man-made accelerators too. If the above condition is not satisfied, then the particle would escape out of the accelerator and no further acceleration would be possible. This condition gives

$$E \lesssim 0.5\beta 10^{18} Z(R/\mathrm{kpc})(B/10^{-6}\,\mathrm{G})\,\mathrm{eV}\,, \quad \ldots(1)$$

where $\beta \leq 1$ is a phenomenological "efficiency" factor incorporating, among other things, the fact that the effective magnetic field (e.g., its locally transverse component) in the acceleration process may be less than the ambient field. Interestingly, eq.1 also follows from detailed considerations of the shock-acceleration process, in which the parameter β appears as the velocity of the shock front in units of c.

Eq.1 generally overestimates the maximum energy because it does not take into account the finite lifetime of the accelerator (for example, the shock would generally fade away over some large but finite time scale), and also it does not include the effect of energy loss of the particles (for example, through synchrotron radiation) even as they are accelerated. However, it turns out that even under the optimistic assumption of no energy loss of the accelerated particles within the source, there are hardly any known astrophysical objects with realistically expected values of R and B that can satisfy eq.1 for $E \gtrsim 1\,\mathrm{ZeV}$.

An obvious alternative way of producing sufficiently high energy particles is provided by the so-called "top–down" scenario in which the UHECR particles owe their origin to decay of some supermassive "X" particles of mass $m_X \gg 100\,\mathrm{EeV}$, so that their decay products, envisaged as the UHECR particles, can have energies all the way up to $\sim m_X$. Thus, no acceleration mechanism is needed. The sources of the massive X particles could be topological defects such as cosmic strings or magnetic monopoles that could be produced in the early Universe during symmetry-breaking phase transitions envisaged in Grand Unified Theories (GUTs). In an inflationary early Universe, the relevant topological defects could be formed at a phase transition at the end of inflation. Alternatively, the X particles could be certain supermassive metastable relic particles of lifetime comparable to or larger than the age of the Universe, which could be produced in the early Universe through, for example, particle production processes associated with inflation. Absence of nearby powerful astrophysical objects such as AGNs or radio galaxies is not a problem in the top-down scenario because the X particles or their sources need not necessarily be associated with any specific active astrophysical objects. In certain models, the X particles themselves or their sources may be clustered in galactic halos, in which case the dominant contribution to the UHECR observed at Earth would come from the X particles clustered within our Galactic Halo,

For a comprehensive review and references to literature on the top-down scenario, see, e.g. ref.[5].

Extragalactic Sources and the Problem of "GZK Cutoff"

The propagation of UHECR particles originating from extragalactic sources is strongly affected by the presence of the 2.7K cosmic microwave background (CMB) as was first pointed out by Greisen and independently by Zatsepin and Kuzmin[12]. Consider a collision between a nucleon of energy, say, $\sim 10^{20}$ eV, and a CMB photon of typical energy $\sim 10^{-3}$ eV (as measured in the CMB rest frame, defined as the frame in which CMB is isotropic). In the rest frame of the nucleon, the CMB photon would, depending on the angle of collision, appear as a γ-ray of energy up to about 200 MeV (for a head-on collision). Such a collision would thus have enough energy to produce a pion. For a CMB photon of energy ε, the threshold nucleon energy for this photo-pion production process is given by

$$\begin{aligned} E_{th} &= \frac{m_\pi(m_N + m_\pi/2)}{\varepsilon} \\ &\simeq 6.8 \times 10^{19} \left(\frac{\varepsilon}{10^{-3}\,\mathrm{eV}}\right)^{-1} \mathrm{eV}, \quad \ldots(2) \end{aligned}$$

where m_N and m_π are the nucleon and pion mass, respectively. The total cross section for photo-pion production is dominated by the well-known Δ resonance which occurs near the threshold for single pion production. The cross section at the resonance is $\sim 5 \times 10^{-28}\,\mathrm{cm}^2$. The collision length for photo-pion production by nucleons of energy above $\sim$100 EeV off CMB photons is roughly energy independent and $\sim$6 Mpc (see, e.g., ref.[5]). In addition, this process is a drastic energy loss channel for the nucleon — it loses about one-fifth of its energy on average to the pion in each interaction. Detailed calculations show (see, e.g. ref.[21]) that the observed energy of a nucleon at Earth, from a source at a distance $\gtrsim$ 100 Mpc, will always be less than 10^{20} eV, irrespective of the energy ($\geq 10^{20}$ eV) at the source. Nuclei and γ-rays above 10^{20} eV have similar energy attenuation length scales; nuclei are photo-disintegrated in the CMB as well as in the infrared (IR) background, while photons are absorbed due to e^+e^- pair production off the radio background photons. For detailed discussions and review of propagation of UHECR particles, see, e.g., ref.[5].

The above considerations imply that the UHECR spectrum should show a *cutoff* — the GZK cutoff — somewhere in the region of $\sim$ 70–100 EeV, if the sources are not too strongly clustered in our cosmological neighbourhood.

As already mentioned above, observationally, the situation with regard to the presence or absence of the GZK cutoff is rather ambiguous at present, and must await results from the Auger experiment for resolution in the next few years. It cannot be overemphasized that the confirmation of the presence or absence of the GZK feature is crucial to unraveling the mystery of the origin of UHECR. If the presence of GZK cutoff is confirmed, it would imply that the sources of the observed UHECR above a few tens of EeV mostly lie at large ($\gg$ 100Mpc) cosmological distances from Earth. The confirmed absence of a cutoff would, however, be much more difficult to understand and may require rather special configurations of large-scale magnetic fields associated with the local large-scale matter distribution to produce the observed isotropy of the flux from a relatively few sources in our cosmological neighbourhood (see. e.g., ref.[7] for a review of this possibility). Alternatively, one may have to invoke scenarios involving neutrinos discussed in the next two sections, or even more exotic possibilities of new particles propagating unattenuated from cosmologically distant sources, or Lorentz symmetry violation, etc; for a review of these "exotic" possibilities, see, e.g. refs.[5-7].

Even if the GZK cutoff problem is resolved by some of the proposed solutions mentioned above, the pressing problem of difficulty of producing the so-called "post-GZK" (i.e., > 100 EeV) events remains with us. As mentioned above, one way to solve the energy problem rather trivially is offered by the top-down (TD) scenario. The TD scenario is, however, also subject to a variety of observational constraints[5]. The major difficulty is that it is not possible at present to reliably calculate the absolute level of UHECR flux contributed by any specific TD mechanism because this involves new physics at energy scales way beyond those currently accessible in the laboratory, for example, near GUT energy scale of $\sim 10^{16}$ GeV, about which we do not have any direct knowledge. At the same time, it is interesting to note that UHECR data have the potential to probe possible new physics at, for example, GUT energy scale.

The TD scenario may be broadly divided into two classes: In the "Galactic Halo" TD scenario[22,23] in which the X particles are some superheavy relic particles clustered within our Galactic Halo, the GZK cutoff should be completely absent and the post-GZK UHECR should be dominated by photons rather than protons. In contrast, in the "universal" TD scenario, in which the X particles arise from collapse, annihilation or other processes involving cosmic topological defects such as cosmic strings, monopoles, and so on, uniformly distributed throughout the Universe, the GZK effect does not lead to a complete cutoff of the spectrum; rather there is a *partial* cutoff at a few tens of EeV followed by[5,24] a "recovery" at somewhat above $\sim$ 100EeV. Also, in the universal TD scenario, the post-GZK UHECR, under generic circumstances, should be dominated by photons rather than protons, although, unlike in the Galactic Halo case, a proton dominated post-GZK UHECR is not necessarily inconsistent with TD scenario depending on the unknown level of the universal radio background in the Universe which determines the propagation of > 100EeV photons in the Universe (see, e.g., ref.[5]). Both TD scenarios, however, produce significantly higher fluxes of UHE neutrinos than what is expected in the bottom-up scenario in general, which may be a crucial test of the TD scenario in general because such high neutrino fluxes are potentially detectable by upcoming experiments such as Auger and EUSO. There are other tests of both versions of the TD scenario, which are described in detail, e.g., in refs.[5-7].

3 Massive Neutrino and the Z-Burst Scenario of UHECR

As clear from the discussions above, while the origin of UHECR in general is unknown, explaining the post-GZK UHECR events is a particularly difficult problem to solve because of the absence of any candidate astrophysical sources within the so-called GZK distance limit of ~ 100Mpc. In this and the following sections we, therefore, focus particularly on the issue of origin of these post-GZK events.

The only particle in the Standard Model (SM) that can propagate unattenuated with energies above 10^{20}eV from sources at distances $\gg 100$Mpc is the neutrino; however, in the SM, the probability of neutrinos to directly initiate the observed UHECR air-shower events is at least a factor of $\sim 10^{-6}$ smaller than the corresponding probability in the case of nucleons. However, as first suggested in ref.[9], neutrinos of sufficiently high energy from cosmologically distant ($\gg 100$Mpc) sources can *indirectly* give rise to the observed post-GZK UHECR events.

The idea hinges on allowing one of the most conservative deviations from the SM, namely, that neutrinos have small masses in the sub-eV to eV range, which is strongly supported by experimental evidence[25] of atmospheric neutrino flavor oscillation. If some flavor of neutrino is assumed to have a small mass $m_\nu \sim 1\,\text{eV}$, and if there are sources capable of producing neutrinos of sufficiently high energy ($\gtrsim 10^{22}$eV), then interaction of those neutrinos with the neutrinos (ν_b) constituting the cosmic thermal neutrino background (CTNB) (the neutrino equivalent of the CMBR) can excite the Z boson resonance, $\nu + \bar{\nu}_b \to Z$, for a UHE neutrino energy $E_{\nu,\text{res}} = (M_Z^2/2m_\nu) \simeq 4 \times 10^{21}(\text{eV}/m_\nu)\text{eV}$, where $M_Z = 91\,\text{GeV}$ is the Z-boson mass. The decay of each Z (rest-frame life time $\sim 3 \times 10^{-25}$ sec) into $q\bar{q}$, the branching ratio for which is $\sim 70\%$, and the subsequent hadronization of the quarks would produce about one nucleon-antinucleon pair, 10 neutral pions and 17 charged pions[26] with neutral pions further decaying into photons and charged pions into neutrinos, electrons and positrons. It has been suggested[9] that the resulting UHE nucleons and photons from the decay of the Z bosons produced *within the GZK distance limit of* $\sim$ 100 Mpc *from Earth* could be candidates for the observed post-GZK UHECR events. In this so-called Z-burst scenario, since the final decay products of the Z are dominated by photons and neutrinos, the post-GZK UHECR events are predicted to be mainly photons (like in the top-down scenario in general discussed above) rather than nucleons.

Note that for massless neutrinos, the required UHE neutrino energy would be much higher: $E_{\nu,\mathrm{res}}(m_\nu = 0) \simeq 8 \times 10^{24}(4.8 \times 10^{-4}\,\mathrm{eV}/\varepsilon_{\nu,b})\,\mathrm{eV}$, where $\varepsilon_{\nu,b} \simeq 3T_\nu$ is the typical energy of the CTNB neutrino, $T_\nu \simeq 1.9\mathrm{K} \approx 1.6 \times 10^{-4}\,\mathrm{eV}$ being the effective temperature of the CTNB. Such high energy neutrinos are unlikely to be produced in any astrophysical sources.

The invariant energy-averaged cross section for the process $\nu + \bar{\nu}_b \to Z$, defined as $\langle\sigma\rangle \equiv \int ds\sigma(s)/M_Z^2$, with s the square of the energy in the center of momentum frame, is $\langle\sigma\rangle \simeq 4.2 \times 10^{-32}\,\mathrm{cm}^2$. The relative energy width of the Z resonance at FWHM is $\sim$3%. So, only UHE neutrinos with energy in a small range around the resonant energy $E_{\nu,\mathrm{res}}$ are involved in producing the Z's. Because the target background neutrinos (of mass in the eV range) are essentially nonrelativistic, the produced Z-boson has the energy $E_Z \simeq E_{\nu,\mathrm{res}}$. The average nucleon energy in the Z decay is $\langle E_N\rangle \sim E_{\nu,\mathrm{res}}/30 \sim 1.3(\mathrm{eV}/m_\nu) \times 10^{20}\,\mathrm{eV}$ while the average photon energy $\langle E_\gamma\rangle \sim 0.5\langle E_N\rangle$, since the total particle multiplicity in the Z decay is about 30 and each pion decays into two photons. For $m_\nu \lesssim 0.1\,\mathrm{eV}$, the produced nucleons and photons can be well above the GZK cutoff and can in principle explain the observed post-GZK events.

Detailed calculations have been done examining the viability of and constraints on the Z-burst scenario; see e.g. refs.[27-31]. The major constraints on the scenario are discussed below.

The probability for resonant annihilation of a UHE neutrino with a background (anti)neutrino of small but finite mass producing Z bosons within a distance $D_{\mathrm{GZK}} \lesssim 100\,\mathrm{Mpc}$ is rather small, $\sim 2.5 \times 10^{-4}$, for a uniformly distributed neutrino background (see, e.g. ref.[32]). The massive neutrinos would, however, be expected to cluster gravitationally, and depending on the length-scale and strength of the clustering, the above probability can be somewhat larger[32], though perhaps not larger than about 1%. In general, because of the relatively small probability of the process, a rather large UHE neutrino flux is required in order to successfully explain the post-GZK UHECR events. This neutrino flux, when extrapolated to lower energies of order $10^{17}\,\mathrm{eV}$ with a spectrum going as E^{-2} expected from typical astrophysical sources, generally conflicts with the limit on neutrino flux[33] at $> 10^{17}\,\mathrm{eV}$ obtained from non-observation of horizontal air-showers that could be initiated by the neutrinos. The conflict can be avoided[29] if the source neutrino spectrum is rather hard[29], $dN_\nu/dE_\nu \propto E_\nu^{-\gamma}$ with spectral index $\gamma \lesssim 1.2$. Such hard spectra of neutrinos are, however, not usually expected from astrophysical sources, but are possible in TD scenario[5].

It has also been pointed out[27] that in the Z-burst scenario, in addition to the requirement of relatively hard spectrum neutrino sources, significant local neutrino clustering is required to avoid generating a diffuse background of 30 MeV to 100 GeV photons in excess of that measured by the EGRET experiment[34]. This comes about in the following way: While the contribution to the observed post-GZK UHECR would come only from Z-bursts occurring in our cosmological neighborhood within $\lesssim 100\,\mathrm{Mpc}$, the accompanying electromagnetic energy injected into the Universe by the sources that produce the relevant UHE neutrinos as well as the electromagnetic component of the Z-bursts themselves at large cosmological distances ($\gg 100\,\mathrm{Mpc}$) would cascade down to lower energies through the process of electromagnetic cascading in the cosmological radiation background fields (see, e.g. ref.[5] for review of the cosmological electromagnetic cascading process), and would thus give rise to a diffuse gamma ray background peaking at around 10 GeV. A relatively lower flux of Z-burst-initiating UHE neutrino flux, as would obtain in the case of a local clustering of the relic neutrinos relative to the no-clustering case, would yield a correspondingly lower level of the diffuse gamma ray background in the MeV–GeV region. The analysis of ref.[27] shows that in order for the Z-burst scenario of UHECR origin to be consistent with the EGRET bound on diffuse gamma ray flux in the 30 MeV–100 GeV region, the relic neutrino overdensity f_ν over a length scale l_ν has to satisfy $f_\nu \gtrsim 10^3(l_\nu/5\,\mathrm{Mpc})^{-1}$, if the total photon luminosity of the sources is comparable to their total neutrino luminosity, as would be expected in most source models.

Furthermore, if the UHE neutrinos causing the Z-bursts are produced in astrophysical sources, where they would presumably be produced through interaction of accelerated protons with the dense matter and radiation in the source, then those sources must be such as to trap the accelerated protons within the sources because otherwise the observable proton flux below the GZK cutoff would be comparable to the neutrino flux[35,36] in contradiction with observation. In other words, in order for the Z-burst mechanism to contribute significantly to the observed UHECR flux, the existence of a new class of high energy neutrino sources, possibly unrelated to the sources of $> 10^{19}$ eV cosmic rays, may have to be invoked. Moreover, it has been argued[36] that the energy generation rate of these UHE neutrino sources would have to be comparable to the total photon luminosity of the Universe.

In this context, it has been pointed out[37] that a degenerate relic neutrino background with a finite neutrino chemical potential (implying an asymmetry between ν and $\bar{\nu}$), produced, for example, through neutrino flavor oscillation in the early Universe, would allow a much larger density of the Fermi-degenerate relic neutrinos than is predicted in the standard big bang model, and would consequently increase the neutrino annihilation- and thus Z boson production probability. Authors of ref.[37] have argued that for $m_\nu \simeq 0.07$ eV, the value suggested by the Super-Kamiokande experiment[25], and for a background neutrino density parameter $\Omega_\nu \simeq 0.01$, the resulting requirement on the source UHE neutrino flux (in order to explain the observed post-GZK UHECR flux observed by AGASA) implies energy generation rate of the UHE neutrino sources well below the total photon luminosity of the Universe.

If the post-GZK UHECR events are indeed due to the Z-burst mechanism, then it offers the exciting possibility of *determining* the mass of the heaviest neutrino, as pointed out in ref.[38] and studied in more detail in ref.[30], by fitting the predictions of the Z-burst scenario to the observed UHE CR data. The neutrino mass so determined[30] from the present data is consistent with the value indicated by the Super-Kamiokande experiment[25]. Note, however, that for such neutrino masses, the sources are required to produce neutrinos at least up to 10^{22} eV for the Z-burst mechanism to work. Such high energies are rather difficult to obtain within conventional bottom-up models, but are easily obtained in top-down models, making the Z-burst scenario more likely to play a role in the latter.

4 New Neutrino Interactions

As mentioned above, because of their very weak interaction with matter in the SM, the neutrinos are unlikely to directly initiate the air-showers with the characteristics of the observed UHECR air-shower events. It has, however, been suggested that the neutrino-nucleon interaction cross section could be enhanced significantly at centre-of-mass (CM) energies higher than the electroweak scale or above about a PeV in the nucleon rest frame by new physics effects beyond SM. The enhanced νN cross section, if it reaches $\sim 100 - 200$ mb, could then allow neutrinos themselves to directly initiate the air showers responsible for the post-GZK UHECR events. Most of these suggestions violate the unitarity of cross section[39]. However, two major unitarity-respecting possibilities have been suggested. In one of these schemes, there is a broken local SU(3) "generation symmetry" dual to the SU(3) colour symmetry. In this scheme, neutrinos can have effectively strong interaction with quarks and, in addition, neutrinos can interact coherently with all partons in the nucleon, resulting in an effective cross section comparable to the geometrical nucleon cross section[40]. However, the massive neutral gauge bosons of the broken generation symmetry would also mediate flavor changing neutral current (FCNC) processes, and experimental bounds on these processes indicate that the scale of any such new interaction must be above ~ 100 TeV.

The second possibility is that there may be a large increase in the number of degrees of freedom above the electroweak scale (see, e.g., ref.[41]). A specific implementation of this idea is realized in theories with n additional "large" compact dimensions and a quantum gravity scale $M_{4+n} \sim$ TeV, a possibility that has recently received much attention in the literature[42], especially within the context of string theories. In these theories, the SM particles are confined to the usual 3+1 dimensional space and only gravity propagates in the higher dimensional space. The typical size of the compact extra dimensions (assuming same for all the extra dimensions) R_n is related to the fundamental scale M_{4+n} through the relation $R_n \simeq M_{4+n}^{-1}(M_{\rm Pl}/M_{4+n})^{2/n}$, where $M_{\rm Pl} = 1.2 \times 10^{19}$ GeV is the usual Planck energy. For $M_{4+n} \sim$

TeV, the $n = 1$ case is obviously ruled out, but higher n's are not. From a 4-dimensional point of view, the $4 + n$-dimensional graviton appears as an infinite tower of Kaluza-Klein (KK) excitations. The exchange of these KK modes, whose large number compensates for the weakness of the gravitational coupling, gives extra contribution to any 2-particle cross section that increases rapidly with energy. It has been suggested[41, 43, 44] that the resulting enhanced νN interaction cross section may make neutrinos responsible for the observed post-GZK UHECR events. Constraints on this scenario from the existing data and projected data from future experiments are discussed in ref.[45].

Further detailed calculations[46] of the contribution of the KK modes to the enhanced νN cross section, however, show that the resulting cross section and the average energy transfer in each νN interaction are still too small to explain the observed vertical UHECR showers, although the new interaction could give rise to deeply penetrating showers or horizontal air showers which are so far unobserved but may be observed in future detectors such as the Auger.

There are also independent astrophysical constraints on M_{4+n} resulting from limiting the emission of KK gravitons into the extra dimensions. The strongest constraints in this regard come from nucleon-nucleon bremsstrahlung in type II supernovae[47], which give $M_6 \gtrsim 50\,\mathrm{TeV}$, $M_7 \gtrsim 4\,\mathrm{TeV}$, and $M_8 \gtrsim 1\,\mathrm{TeV}$, for $n = 2,3,4$, respectively. Thus, it is hoped, the up-coming large area UHECR detectors together with various astrophysical and cosmological constraints will be able to provide stringent constraints on these theories with large extra dimensions. For a more detailed review, see, e.g., the article by G. Sigl in ref.[7].

Summary and Conclusions

The solution of the UHECR enigma seems to require some kind of new physics beyond the Standard Model, either to solve the problem of energetics (i.e., production of particles of energy $> 10^{21}$ eV) or to solve the problem of absence of sufficiently powerful identifiable astrophysical sources in the nearby Universe. We have discussed above two ideas regarding the possible role of neutrinos in this problem, both of which were proposed mainly to solve the problem of absence of sufficiently powerful sources of UHECR in our cosmological neighbourhood, since neutrinos can travel unattenuated from distant cosmological sources. Both scenarios are, however, subject to severe constraints from a variety of considerations which we have discussed. The Z-burst scenario requires rather high flux of neutrinos at energies approaching $\sim 10^{23}$ eV, which is therefore, likely to work perhaps only within the context of a top-down model of UHECR. In the scenario involving possible new (almost) strong interaction of neutrinos at the relevant ultrahigh energies due to possible new physics beyond Standard Model, the neutrino interaction is still not strong enough to give rise to the observed post-GZK UHECR showers. However, both of these scenarios predict sufficient flux of UHE neutrinos which should be detectable as horizontal air-showers in the up-coming experiments such as Auger and/or EUSO. The up-coming and proposed future UHECR experiments thus have the potential to probe possible new-physics beyond the SM suggested in this context.

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