POSSIBILITY TO DETECT THE COSMIC NEUTRINO BACKGROUND WITH EECR NEUTRINOS

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ABSTRACT

Standard Cosmology (hot Big-Bang) together with the Standard Model (SM) of particle physics predict the existence of a cosmic neutrino background ($C\nu B$), liberated from the primordial plasma when the Universe was just one second old. The predicted temperature of the $C\nu B$ today is $T_\nu = 1.95K$, the neutrino mean momentum is $\sim 3T_\nu$, and the neutrino mean density per spin state per mass state is 54 cm^{-3}. Verification of the $C\nu B$ is a formidable experimental challenge. After reviewing properties of the $C\nu B$, I examine the most promising proposal for measuring the $C\nu B$, namely resonant absorption on the $C\nu B$ of extreme-energy cosmic-ray (EECR) neutrinos at energy $E_j^R = \frac{M_Z^2}{2m_{\nu_j}} = 4\left(\frac{\mathrm{eV}}{m_{\nu_j}}\right)\times 10^{21}$ eV. In addition to leaving a dip in the neutrino flux, the absorption also produces a highly-boosted ($\gamma \sim 10^{11}$) Z-boson which decays to a "Z-burst" of particles including many photons and a few nucleons. Z-bursts may be the source of the air-shower events observed with energy above the GZK limit of $\sim 5\times 10^{19}$ eV. If so, we may infer (i) that one or more neutrino masses lies in the 0.1 to 1 eV range, a value consistent with the masses inferred from oscillation experiments; and (ii) there is a large neutrino flux at $\sim 10^{22}$ eV which can be measured in proposed experiments such as EUSO and OWL.

1. The Cosmic Neutrino Background (CνB)

The discovery of the cosmic microwave background (CMB) radiation in 1966 had a tremendous impact on modern cosmology. First of all, the nearly perfect thermal Planck spectrum told us that the Universe was once at least as hot as the plasma temperature of hydrogen, $\sim$ eV, or $\sim 10^4$ K. Secondly, the measured temperature of $T_\gamma = 2.73$K provided a normalization point for the theoretical curves relating energy-density to scale-size (redshift) to temperature.

A more challenging validation of the hot Big-Bang model would be the measurement of the cosmic neutrino background ($C\nu B$). The $C\nu B$ is predicted to have been part of the thermally-equilibrated plasma at much earlier times and much higher temperatures. Neutrinos became free-streaming when their interaction rate fell below the expansion rate $H(t)^{-1}$ ($H(t)$ is the Hubble parameter). Because neutrinos interact so weakly, this occurred when the Universe was but a second old,[a] and the temperature was $\sim$ MeV, some 10^{10} times hotter than today. Coincidentally, the era of neutrino decoupling and the era of Big-Bang nucleosynthesis (BBN) are the same.

[a]We consider only active neutrinos with SM weak interactions.

Once decoupled, the neutrino number remained fixed, while the individual neutrino momenta continued to redshift by a factor of 10^{-9} to lower values. For neutrino flavors which were relativistic at decoupling, i.e. ν_e, ν_μ, and ν_τ which are made up of rest masses below $\sim$ MeV, the net effect is to retain a relativistic Fermi-Dirac momentum-distribution, but with temperature redshifted. There is a subtlety. Subsequent to neutrino decoupling, e^+e^- annihilations produced cosmic photons but not neutrinos, thereby raising the CMB temperature relative to the neutrino temperature by the factor $(11/4)^{1/3} = 1.4$. Thus, Big-Bang cosmology makes a firm prediction that today's $C\nu B$ has a momenta profile given by a relativistic Fermi-Dirac distribution with an effective temperature of $T_\nu = T_\gamma/1.4 = 1.95$K.

Oscillation experiments indicate that the mass basis and the flavor (interaction) basis of neutrinos do not coincide. In general, the flavor states are unitary mixtures of the mass states, and vice versa. Letting $\alpha = e, \mu, \tau$ label flavor and $j = 1, 2, 3$ label mass, one has $|\nu_\alpha >= \sum_j U_{\alpha j}|\nu_j >$ and $|\nu_j >= \sum_\alpha (U^\dagger)_{j\alpha}|\nu_\alpha >$, where U is the unitary mixing matrix. Indications from the solar and atmospheric neutrino experiments are that the mixing factors are large; e.g., in the presently popular "bi–maximal" model[1)], all the $|U_{\alpha j}|^2$ factors except for $|U_{e3}|^2$ are in the range 0.25 to 0.5. Flavor mixing affects the present density of relic mass eigenstates, giving $n_{\nu_j} = \sum_\alpha |U_{\alpha j}|^2 n_{\nu_\alpha}$, where $\sum_\alpha$ is a sum over the three neutrino flavors and n_{ν_α} is the ν_α relic density expected in the absence of mixing. This formula results from the separation ("decoherence") of the neutrino wave function into distinct wave packets for each mass eigenstate after a Hubble–time of travel. Note, however, that if the three n_{ν_α} are the same, $\equiv n_\nu$, as might be expected from a high-temperature thermal population, then unitarity gives $n_{\nu_j} = n_\nu$ for all three mass states $j = 1, 2, 3$. In what follows we will assume $n_{\nu_\alpha} = n_\nu$ for the three light flavors, which implies a common momentum distribution for each light mass-state, and a common n_{ν_j}.

Integrating over the momentum distribution, one finds for the mean neutrino number density today

$$\langle n_{\nu_j} \rangle = \frac{3\,\zeta(3)}{4\pi^2}\, T_\nu^3 = 54\,\mathrm{cm}^{-3} \tag{1}$$

for each light ($<$ MeV) neutrino, with an equal number density for each antineutrino. The value of $\zeta(3)$ is $1.202\ldots$. Since the predicted relic–neutrino density is normalized to the measured relic photon density, the predicted mean density of neutrinos (in the absence of a neutrino chemical potential - more on this later) must be considered firm.

In a Universe apparently made of matter rather than antimatter, it may seem odd to find an abundance of antineutrinos as well as neutrinos. The reason for this is that the light neutrinos and antineutrinos fell out of thermal equilibrium while still relativistic (hence the name "hot dark matter"). This is in contrast to the electron, proton and neutron, for which the nonrelativistic Boltzmann factor exponentially suppressed the antiparticle.

The experimental and theoretical challenge is to find a means to measure this predicted $C\nu B$. A successful measurement would validate Big-Bang cosmology back to the first second after the Bang.

In this review we will examine the possibility to infer the $C\nu B$ via annihilation of $C\nu B$ neutrinos with extreme-energy cosmic-ray (EECR) antineutrinos, and vice versa. Another approach to seek the $C\nu B$ which shows some promise is the study of the transfer function relating the primal density-fluctuations in the CMB to the observed large-scale structure (LSS) in today's Universe. However, this approach cannot provide as much detail on the $C\nu B$ as is potentially available with the EECR measurements. Ingenious table-top experiments have also been proposed to ascertain the existence of the $C\nu B$. These do not appear to be promising. They are reviewed by S. Pakvasa[2)].

1.1. Possible $C\nu B$ Clustering

As it is momentum (not energy) which redshifts as the Universe expands, the mean momentum of the neutrinos today is $p_\nu \sim 3\,T_\nu \sim 6 \times 10^{-4}$ eV. Consequently, relic neutrinos with a mass exceeding this value are nonrelativistic, having an energy dominated by their rest mass.

We live in a matter-rich portion of the Universe. The Supergalactic Cluster, the Local Group, and the Galactic Halo each provides a "local potential well" which is expected to trap the nonrelativistic neutrinos and thereby enhance the local relic-neutrino density compared to the universal average. One expects the relic neutrinos to be less clustered than the baryons for several reasons. First of all, neutrinos do not dissipate energy as easily as electrically charged protons do. Secondly, neutrinos have a much larger Jeans ("free–streaming") length than do baryons at the crucial time when galaxies start to grow nonlinearly. And thirdly, Pauli blocking presents a significant barrier to clustering of light–mass fermions. As a crude estimate of Pauli blocking, one may use a zero temperature Fermi gas as a model of the gravitationally bound halo neutrinos. Requiring that the Fermi momentum of the neutrinos not exceed the virial velocity $\sigma \sim \sqrt{MG/L}$ within the cluster, one gets the phase space constraint[3)]

$$\frac{n_{\nu_j}}{54\,\mathrm{cm}^{-3}} \lesssim 10^3 \left(\frac{m_{\nu_j}}{\mathrm{eV}}\right)^3 \left(\frac{\sigma}{200\mathrm{kms}^{-1}}\right)^3 . \qquad (2)$$

The same constraint holds for $n_{\bar{\nu}_j}$. The virial velocity within our Galaxy is a couple hundred km/sec, whereas virial velocities for rich galactic clusters are a thousand km/s or more. Thus it appears that Pauli blocking allows significant clustering on the Galactic scale only if $m_\nu \gtrsim 1$ eV, but allows clustering on the larger scales for $m_\nu \gtrsim 0.1$ eV. (We will see that eV and 0.1 eV masses are each allowed by present neutrino oscillation data.) The free–streaming argument also favors clustering on the larger scales.

1.2. Possible CνB Asymmetry

A further enhancement of the neutrino density arises if the Universe possesses a net neutrino number. Baryon number and lepton number are not conserved quantities in the Standard Model (SM) of particle physics, due to coherent processes at the electroweak symmetry–breaking scale. Thus, in general, one does not expect exact particle-antiparticle number symmetry. The observed baryon asymmetry in the Universe is $\Delta B \equiv (n_B - n_{\bar{B}})/n_\gamma \sim 10^{-9}$. Since the baryons are primarily protons, charge neutrality requires a similar asymmetry for the electron-positron system. The neutrino asymmetry is unknown, and poorly bounded by observation.

In terms of the degeneracy parameter $\xi \equiv \mu/T$ appearing in the Fermi-Dirac distribution function, the neutrino asymmetry is

$$\Delta\nu \equiv \frac{(n_{\nu_j} - n_{\bar{\nu}_j})}{n_\gamma} = 0.025\,(\pi^2\xi + \xi^3). \tag{3}$$

Any neutrino-antineutrino asymmetry (parameterized by a nonzero ξ) increases the sum of the neutrino plus antineutrino relic densities. With a large degeneracy parameter, the thermal equilibrium distributions are such that the density of one species (n_{ν_j} or $n_{\bar{\nu}_j}$) is suppressed exponentially in ξ while the density of the other is enhanced as a power–law in ξ. Studies of galaxy formation and primordial nucleosynthesis lead to the bounds[4)] $-0.06 \lesssim \xi_{\nu_e} \lesssim 1.1$ and $|\xi_{\nu_{\mu,\tau}}| \lesssim 6.9$. These bounds on ξ translate into $\Delta\nu_e \lesssim 0.3$, which is modest, and $\Delta\nu_{\mu,\tau} \lesssim 10$, which is large. The latter bound allows an enhancement in $n_{\nu_{\mu,\tau}}$ or $n_{\bar{\nu}_{\mu,\tau}}$ by a factor up to 80.[b]

Note that although the two spin states of Majorana neutrinos are not particle and antiparticle, the same thermodynamic counting that applies to Dirac neutrinos applies also to Majorana neutrinos. Consequently, the asymmetry and density enhancement that result from the calculation apply to both kinds of neutrino. The calculation is common because the two Majorana spin states, when relativistic, can annihilate only with each other like particle and antiparticle, owing to the helicity conserving nature of the vector and axial vector weak interaction in the relativistic limit. Once a density asymmetry or enhancement is fixed at the time of decoupling, it cannot change during free expansion.

2. Scattering on the CνB

Consider the scattering of particles on the *CνB* as a means to indirectly "see" the *CνB*. The history of this endeavor begins in 1982,[5)] when it was shown that the

[b] Of course, ξ cannot be so large that Ω_ν exceeds the bound deduced from large–scale structure formation. Since $\xi^3\,(m_\nu/\mathrm{eV}) = 430\,\Omega_\nu\,h_{65}^2$ is valid for $m_\nu/T_\nu \gg \xi \gg 1$, we have from the overall density budget $\Omega_\nu\,h_{65}^2 \lesssim 0.15$ that $\xi^3\,(m_\nu/\mathrm{eV}) \lesssim 65$.

best signature by far is a measurement of absorption features (dips) in the extreme-energy spectrum of cosmic-ray neutrinos, due to annihilation with the $C\nu B$ on the Z-resonance. Even more promising[6,7] may be detection of emission features (Z-bursts) as particles above the famed GZK-cutoff at $E_{\rm GZK} \sim 5 \times 10^{19}$ eV (to be discussed in a later section).

At decoupling, the $C\nu B$ neutrinos are left-handed and the $C\nu B$ antineutrinos are right-handed, owing to the chiral nature of the weak interaction. However, $C\nu B$ neutrinos which are nonrelativistic today are unpolarized. This means that all spin states are equally populated today. If the neutrino is a Dirac particle, then the densities of the "wrong-helicity" or "sterile" ν_R and $\bar{\nu}_L$ are equal to the densities of the two active states ν_L and $\bar{\nu}_R$. Therefore, for Dirac neutrinos the active densities available for scattering are half of the total densities. For Majorana neutrinos, there are no sterile fields and the total densities are active in scattering. In what follows we will present cross-sections for a $C\nu B$ of Majorana neutrinos (favored by model builders). If the neutrinos are Dirac instead, then the cross-sections will be reduced by one-half.

2.1. Terrestrial Accelerator Beams Scattering on the $C\nu B$

Since the $C\nu B$ fills all space, including the beam pipe vacuum of an accelerator, one could imagine scattering directly on the $C\nu B$ with an accelerator beam. However, cross-sections for this at conceivable cms energies $\sqrt{s}$ are incredibly small. For example, looking for scattered electrons or forward scattered $C\nu B$ neutrinos with a TeV electron linac beam involves the ν-e cross-section

$$\sigma^{\nu e}(\epsilon) \sim \frac{m_e^2\, G_F^2}{8\pi}\, \frac{\epsilon^2}{\epsilon+1}\,, \tag{4}$$

where $\epsilon = 2m_\nu E_e/m_e^2 = 7.7\,\frac{m_\nu}{\rm eV}\,\frac{E_e}{\rm TeV}$. The prefactor in eq. (4) is of order one, with its exact value depending on whether the neutrino is a ν_e or a ν_μ or ν_τ. Even with a TeV linac and a 1 eV neutrino mass, the cross-section is only a few times 10^{-45} cm^2. For perspective, this yields a scattering rate in a linac of length L with electron current I of

$$R^{\nu e} = \left(\frac{I}{\rm Amp}\right)\left(\frac{L}{\rm km}\right)\left(\frac{n_\nu}{300{\rm cm}^{-3}}\right)\left(\frac{\sigma^{\nu e}}{10^{-44}{\rm cm}^2}\right) \times 10^{-10}/{\rm yr}\,. \tag{5}$$

If recoiling electrons are the signal, there is background from beam-gas scattering. If forward-scattered neutrinos are the signal, then there is a further weak cross-section factor to detect the neutrinos. The scattered neutrinos emerge with nearly the full beam energy, with half of them (from the forward hemisphere in the cms frame) focussed in a small cone of half angle $\theta_\nu \sim \frac{1}{\gamma_\nu} \sim 10^{-12}\frac{TeV}{E_e}\frac{m_\nu}{\rm eV}$. One might imagine several kilometers of fiber optic (length l) as a neutrino detector. Each neutrino interaction in the fiber creates a light flash which could be collected at the far end.

However, the interaction probability in such a fiber is only

$$\frac{l}{\lambda_{\nu N}} \sim \left(\frac{l}{\text{km}}\right)\left(\frac{n_N}{10^{25}\text{cm}^{-3}}\right)\left(\frac{\sigma_{\nu N}}{10^{-35}\text{cm}^2} \sim \frac{E_\nu}{\text{TeV}}\right) \times 10^{-4}\,. \tag{6}$$

There is little hope for direct detection of the $C\nu B$ using terrestrial accelerators. We must turn to the skies for cosmic accelerators.

2.2. Extreme-Energy Cosmic-Ray Scattering on the $C\nu B$

In this section we present cross-section formulae for the scattering of cosmic-ray neutrinos on the $C\nu B$. We ignore effects of order m_l^2/M_W^2 by setting lepton masses (generically, m_l) to zero from the onset.

The cross-section for ν-$\bar{\nu}$ annihilation is

$$\sigma^{\nu\bar{\nu}}_{Z-res}(s) = \frac{4\,G_F\,s}{\sqrt{2}}\;\frac{M_Z\,\Gamma_Z}{(s-M_Z^2)^2+(M_Z\Gamma_Z)^2}\,. \tag{7}$$

Low and high energy limiting cases are

$$\frac{4\,G_F}{\sqrt{2}}\,\frac{\Gamma_Z}{M_Z}\,\frac{s}{M_Z^2} \qquad (s \ll M_Z^2)\,, \tag{8}$$

and

$$\frac{4\,G_F}{\sqrt{2}}\,\frac{\Gamma_Z}{M_Z}\,\frac{M_Z^2}{s} \qquad (s \gg M_Z^2)\,. \tag{9}$$

The Z-mass and width are $M_Z = 91.2$ GeV and $\Gamma_Z = 2.49$ GeV, and $G_F = 1.17 \times 10^{-5}\,\text{GeV}^{-2}$ is the Fermi constant, related to more fundamental quantities by

$$\frac{G_F}{\sqrt{2}} = \frac{g_2^2}{8M_W^2} = \frac{\pi\,\alpha}{2\sin^2\theta_W M_W^2}\,. \tag{10}$$

A useful relation is

$$\frac{\Gamma_Z}{M_Z} = \frac{G_F}{\sqrt{2}}\,\frac{M_Z^2}{12\pi} = 2.2\%\,. \tag{11}$$

The laboratory energy of the neutrino annihilating at the peak of the Z–pole is

$$E_j^R = \frac{M_Z^2}{2m_{\nu_j}} = 4\left(\frac{\text{eV}}{m_{\nu_j}}\right) \times 10^{21}\,\text{eV}\,. \tag{12}$$

At a given resonant energy E_j^R, only relic neutrinos with the j^{th} mass m_{ν_j} may annihilate. (We will sometimes use E_R generically for resonant energy with the understanding that there are really three different resonant energies, one for each neutrino mass.) The invariant energy–averaged annihilation cross section for the process $\nu_j + \bar{\nu}_j \to Z$ is given by the following integral over the Z pole:

$$\langle\sigma_{Z-res}\rangle \equiv \int \frac{ds}{M_Z^2}\sigma_{Z-res}(s) = \frac{4\pi G_F}{\sqrt{2}} = 4.2 \times 10^{-32}\,\text{cm}^2\,. \tag{13}$$

The energy–averaged annihilation cross section $\langle\sigma_{\rm ann}\rangle$ is the effective cross section for all neutrinos within $\frac{1}{2}\delta E_R/E_R = \Gamma_Z/M_Z = 3\%$ of their peak annihilation energy. We refer to neutrinos with energy in the resonant range 0.97 E_R to 1.03 E_R as "resonant neutrinos."

W-exchange in the t-channel contributes to ν-$\bar\nu$ scattering (and not to ν-ν or $\bar\nu$-$\bar\nu$ scattering). The process produces two charged leptons. Hadronic final states result when $\tau^\pm$'s are produced and decay; the hadronic branching ratio of the $\tau^\pm$ is 65%. The charged-current differential cross-section is

$$\frac{d\sigma_W^{\nu\bar\nu}}{dt} = \frac{2\,G_F^2}{\pi}\frac{(u/s)^2}{(1-t/M_W^2)^2}\,. \tag{14}$$

The total cross-section is

$$\sigma_W^{\nu\bar\nu}(s) = \frac{2\,G_F^2 M_W^2}{\pi}\ \left\{1+\frac{2M_W^2}{s}\ \left[1-\left(1+\frac{M_W^2}{s}\right)\ln\left(1+\frac{s}{M_W^2}\right)\right]\right\}. \tag{15}$$

The W mass is $M_W = 80.4$ GeV. The low energy limit for the cross-section is $\frac{2\,G_F^2\,s}{3\,\pi}$. The high-energy asymptotic value is $\frac{2\,G_F^2 M_W^2}{\pi} = 2.2\times 10^{-34}\,{\rm cm}^2$.

For completeness, we give also the elastic cross-sections resulting from Z-exchange in the t-channel. The differential cross-section is

$$\frac{d\sigma_Z^{\nu\bar\nu}}{dt} = \frac{G_F^2}{2\pi}\frac{(u/s)^2}{(1-t/M_Z^2)^2} \tag{16}$$

for ν-$\bar\nu$ scattering (we do not include the s-channel Z-exchange amplitude which contributes when ν-$\bar\nu$ are particle-antiparticle), and the even simpler expression

$$\frac{d\sigma_Z^{\nu\nu}}{dt} = \frac{G_F^2}{2\pi}\ \frac{1}{(1-t/M_Z^2)^2} \tag{17}$$

for ν-ν and $\bar\nu$-$\bar\nu$ scattering (here we do not include the antisymmetrized amplitude which contributes when the two fermions are identical mass or flavor states). The t-channel contributions to the elastic total cross-sections are

$$\sigma_Z^{\nu\bar\nu}(s) = \frac{G_F^2 M_Z^2}{2\pi}\ \left\{1+\frac{2M_Z^2}{s}\ \left[1-\left(1+\frac{M_Z^2}{s}\right)\ln\left(1+\frac{s}{M_Z^2}\right)\right]\right\} \tag{18}$$

and

$$\sigma_Z^{\nu\nu}(s) = \frac{G_F^2 M_Z^2}{2\pi}\ \frac{s}{M_Z^2+s} \tag{19}$$

for ν-$\bar\nu$ and ν-ν ($\bar\nu$-$\bar\nu$) scattering, respectively. At low energies, the cross-section are $\frac{G_F^2\,s}{6\,\pi}$ and $\frac{G_F^2\,s}{2\,\pi}$, respectively, with the ratio $\sigma_Z^{\nu\bar\nu}/\sigma_Z^{\nu\nu}$ equaling one-third in accord with simple helicity arguments. At high energy, both cross-sections approach the same

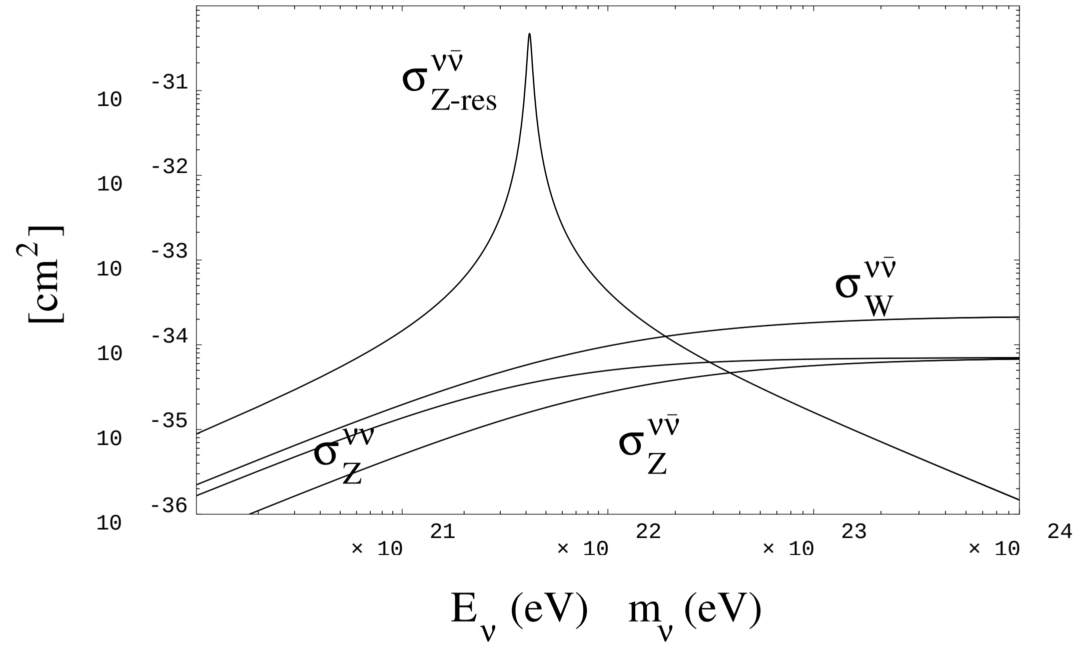

Figure 1: Z-burst and W-exchange cross-sections at energies above E_{GZK}

asymptotic value $\frac{G_F^2 M_Z^2}{2\pi} = 7.0 \times 10^{-35}\,\mathrm{cm}^2$, modulo possible small corrections from running of the couplings and masses in eq. (10). These elastic cross-sections may in principle lead to energy losses for EECR neutrinos.

In Figure (1) we compare the s-channel Z-exchange, t-channel W-exchange, and t-channel Z-exchange cross-sections, plotted as functions of the cosmic-ray energy. At any chosen energy, each curve may be interpreted as the relative fraction of cosmic neutrinos which are scattered by each process. The t-channel W-exchange process has been emphasized in[7], and indeed, the t-channel processes eventually dominate the s-channel process beyond the resonant energy. This is because $\sigma_Z(s)$ falls as s^{-1} above the Z-pole, whereas in the same energy region $\sigma_W(s)$ nearly saturates its asymptotic value. However, the small asymptotic cross-section $\sim 10^{-34}\mathrm{cm}^2$ for σ_W and the (probably) negligible neutrino flux above 10^{22} eV (probably) renders the t-channel scattering uninteresting[5].

Parton scattering on the $C\nu B$ arises from the same charged and neutral t-channel amplitudes as presented here, and so nucleon scattering on the $C\nu B$ is negligible[5].

The scattering rate per solid angle and unit volume of space is given by the product

$$R_\nu(E) = F_\nu(E)\,\sigma_\nu(E)\,n_\nu\,, \tag{20}$$

where $F_\nu(E)$ is the cosmic flux at energy E. Since scattering rates at a given energy are proportional to cross-section times neutrino flux, in Fig. (2) we show the cross-

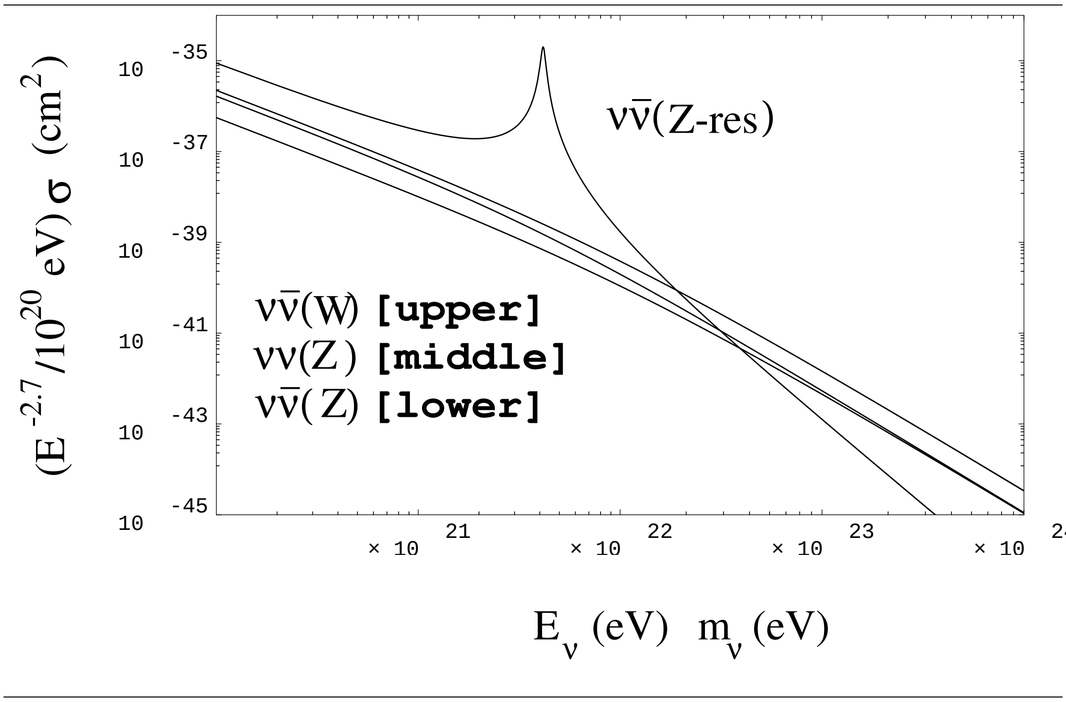

Figure 2: Relative event rates versus energy for an $E^{-2.7}$ cosmic neutrino spectrum.

sections weighted by $E^{-2.7}$ to mimic a typical spectral index of a cosmic flux. Again, at any chosen energy the curves give the relative scattering fractions, but now the relative number of scattering events at two different energies may be gleaned. It is clear that with a typical falling power-law spectrum, the Z-resonance dominates the scattering rate above $E_{\rm GZK}$.

We mention that at even higher energies, there are thresholds for new channels in the SM, such as W^+W^--production[7]. There is also a competitive cosmic-ray process for neutrino scattering on the CMB: $\nu\,\gamma_{2.7K} \to l^- W^+$.[8] At still higher energies yet, there is the possibility of new non-SM $\nu\bar{\nu}$ resonances e.g. Kaluza-Klein modes in low-scale gravity[9]. However, the probable lack of neutrino flux at the energy thresholds for these processes undermines their practical interest.

As explained in §(1.), the nonrelativistic $C\nu B$ is a decoherent ensemble of neutrino mass-eigenstates. The cosmic neutrino flux has also decohered during its Hubble-scale journey. Therefore, scattering takes place between neutrino mass-eigenstates. For Z-exchange amplitudes, this makes no difference as the coupling of the Z is diagonal in either basis, flavor or mass. For W-exchange, there are potentially factors of mixing angles to contend with. For ν_j-$\bar{\nu}_k$ scattering to final lepton flavor α and antilepton β, there is the double projection factor of $|U_{\alpha j}|^2\,|U_{\beta k}|^2$. However, when all final state leptons are included, and all lepton masses are set equal or neglected, the factors sum to $\sum_\alpha |U_{\alpha j}|^2 = 1$. We may then omit any mixing angles from inclusive cross-sections.

The incident fluxes in the mass basis are given by $F_{\nu_j} = \sum_\alpha |U_{j\alpha}|^2 F_{\nu_\alpha}$. For example, the ν_μ's and ν_e's from pion and mu decay will annihilate at the resonant energy of m_{ν_2} with the probability factors $|U_{\mu 2}|^2$ and $|U_{e2}|^2$, respectively, multiplying the cross-sections given above.

3. Resonant Absorption and Emission Features of EECR Neutrinos

It was noted many years ago[5)] that the mean free path (mfp) for a cosmic ray neutrino to annihilate at the Z resonance on the $C\nu B$ is only slightly larger than the Hubble size of the Universe. If neutrinos are nonrelativistic and uniformly distributed throughout the Universe, then the mean annihilation length for resonant neutrinos is

$$\lambda_j = \frac{1}{\langle \sigma_{Z-res}\rangle \langle n_{\nu_j}\rangle} = 4.4 \times 10^{29}\mathrm{cm}\,, \tag{21}$$

which is $30\, h_{65}$ times the Hubble distance $D_H = 1.4\, h_{65}^{-1} \times 10^{28}$ cm; h_{65} is the present value of the Hubble parameter in units of 65 km/s/Mpc. Any cosmic-ray neutrino arriving at earth from a cosmically distant source will have traversed approximately a Hubble distance of space, so its annihilation probability on the relic–neutrino sea is roughly $D_H/\lambda_j = 3.0\, h_{65}^{-1}\,\%$ (independent of m_ν and therefore of E_R). This means that the annihilation probability per cosmic distance of travel may be significant, and that absorption spectroscopy is a possibility in principle for determining neutrino masses[5)]. Inclusion of the effects of cosmic expansion or a neutrino asymmetry can only *increase* the resonant annihilation probability quoted here.

The complementary approach to absorption spectroscopy is emission spectroscopy. Each resonant ν-$\bar{\nu}$ annihilation produces a Z-boson with boost factor $\gamma = E_R/M_Z = M_Z/2m_\nu \sim \frac{10^{11}}{(m_\nu/\mathrm{eV})}$. With a 70% branching ratio, the Z decays into $\langle N\rangle \sim 30$ hadronic particles, including on average two nucleons with mean energy per nucleon

$$\langle E_p\rangle \sim \frac{E_R}{30} \sim 1.3 \left(\frac{\mathrm{eV}}{m_j}\right) \times 10^{20}\mathrm{eV} \tag{22}$$

and ten π^0's which decay into 20 photons with half as much mean energy per photon

$$\langle E_\gamma\rangle \sim \frac{E_R}{60} \sim 0.7 \left(\frac{\mathrm{eV}}{m_j}\right) \times 10^{20}\mathrm{eV}\,. \tag{23}$$

For neutrino masses $\lesssim$ eV, these energies exceed 10^{20} eV. The secondary photons and nucleons produced in the "Z-burst" may even be the primaries for the highest-energy air-showers observed to date. If so, the neutrino mass cannot be too light or the predicted primary energies will exceed the observed event energies. In this way, one obtains for the Z-burst model the approximate 0.1 eV lower limit on the

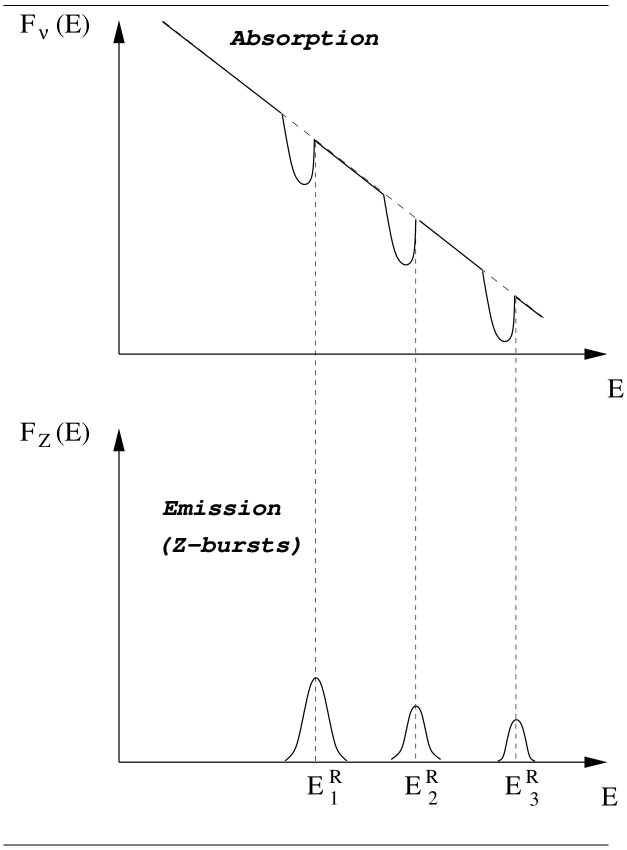

Figure 3: Illustration of the relation between cosmic absorption dips and "local" Z-burst emission.

neutrino mass, when allowance is made for an order of magnitude energy-loss for those secondaries traversing 50 to 100 Mpc.

A schematic drawing of the absorption and emission features in the EECR neutrino spectrum is shown in Fig. (4). The absorption dips are wide compared to the emission lines. The energy range for the dips is E_R to $\frac{E_R}{1+z_{source}}$, as explained below, leading to a width of order $E_R\,\frac{z_{source}}{1+z_{source}}$; z_{source} is the redshift of the EECR-neutrino emitter. the shape of the dips are asymmetric, reflecting evolutionary history of the Universe, also explained below. In contrast, the emission lines are narrow, reflecting the narrow width if the Z-boson ($\Gamma_Z/M_Z = 2.2\%$). Any Z-burst seen at earth must have been produced within 50 to 100 Mpc, and so must have come from the high-energy, non-redshifted edge of the absorption dip; this is illustrated with vertical dotted lines in the figure.

The original resonant annihilation proposal[5)] focussed on absorption spectroscopy, i.e. a measurement of dips in the high energy neutrino spectrum. Measurement of the absorption energies could roughly determine the neutrino masses via $m_{\nu_j} = M_Z^2/2\langle N\rangle E$, where E is a typical observed air–shower energy. High statistics are required to measure absorption dips, for an experiment must map out a range of the spectrum. On the other hand, in the absence of background events, high statistics are not required in emission spectroscopy. In emission spectroscopy, the emitted decay products of the absorbed neutrino are measured directly. The GZK cutoff (to be discussed) prohibits any background events at and above 10^{20} eV. Thus, by collecting events above the GZK cutoff, emission spectroscopy is realized on an event by event basis.

A short annihilation mfp (λ_j) is advantageous for an absorption spectroscopic experiment, in that it enhances the depth of the dips. However, for emission spectroscopy, where the detected particles must arise within the allowed GZK zone, a mfp of order of D_H is optimal — a longer mfp reduces the annihilation rate whereas a shorter mfp reduces exponentially the neutrino flux arriving in the GZK zone. Quantitatively, the probability for a Z–burst per resonant neutrino is the product of the probability for a neutrino to propagate across a distance $\sim D_H$, times the probability to annihilate within the GZK distance, i.e.

$$P(Z-\text{burst}) = (e^{-D_H/\lambda_j})(\frac{D_{\rm GZK}}{\lambda_j}), \quad \text{for} D_{\rm GZK} \ll \lambda_j \,. \tag{24}$$

Writing this burst probability as $(\frac{D_{\rm GZK}}{D_H})(re^{-r})$, where $r \equiv \frac{D_H}{\lambda_j}$, it is easily seen that maximization occurs at $\frac{1}{e}\frac{D_{\rm GZK}}{D_H}$ when $r=1$, i.e. when $\lambda_j = D_H$. This derivation assumes a static universe. The result is altered by the expansion of the universe.

3.1. Cosmic Expansion Effects on Resonant Absorption Dips

Including the effects of expansion, it has been shown[5)] that the survival probability (1− absorption probability) for a cosmic neutrino which arrives at earth with energy $E_{obs} = \frac{E_R}{x}$ from a cosmically-distant source is $e^{-\tau(x)}$; the opacity is given by[c]

$$\tau(x) = \frac{x^3\,\tau_1}{[\Omega_\Lambda + x^3\,\Omega_m + x^2\,\Omega_k]^{\frac{1}{2}}} \tag{25}$$

with support in the interval $1 \le x \le 1+z$. Here Ω_Λ, Ω_m, and Ω_k are the vacuum, matter, and curvature contributions to the Universe's energy density, respectively, and are subject to the constraint $1 = \Omega_\Lambda + \Omega_m + \Omega_k$. We take the curvature to be negligible, i.e. set $\Omega_k = 1$. The constant in eq. (25) is

$$\tau_1 = \frac{4\pi G_F}{\sqrt{2}} n_\nu\, H_0^{-1} = 0.033\, h_{65}^{-1}\,(\frac{n_\nu}{54\text{cm}^{-3}})\,. \tag{26}$$

The allowed range of $x = E_R/E_{obs}$ has a simple interpretation: A neutrino received with energy E left its redshifted source with energy $E(1+z_{source})$, and was a candidate

[c]We update the formula[10)] to include a nonzero cosmological constant parameter Ω_Λ, as is currently-popular.

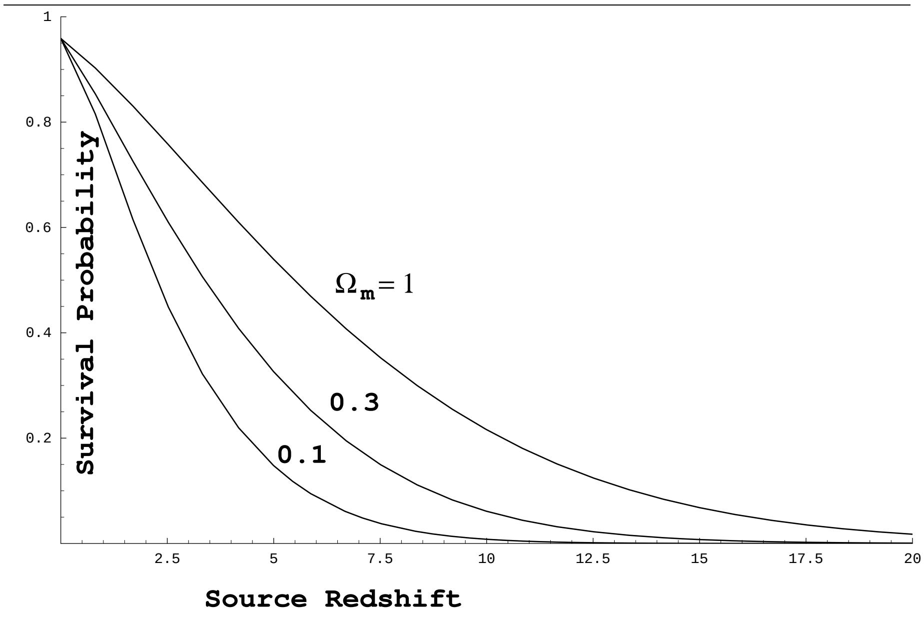

Figure 4: Survival probability for neutrinos emitted with resonant energy from source at cosmological redshift z_e

for annihilation during transit only if the resonant energy xE lay within this energy range, $[E, E(1 + z_{source})]$.

The effect of the Universe's evolution on neutrino absorption is shown in Fig. (4). Plotted is the survival probability $e^{-\tau(x)}$ versus redshift $z = x - 1$. The curves, parameterized by $\Omega_m = 1 - \Omega_\Lambda$, are to be interpreted as follows: Suppose cosmic neutrinos are emitted by a source with redshift $z_{source} = 5$. Then, the portions of the curves with $z \leq 5$ describe the survival probability for these emitted neutrinos to arrive at earth, as a function of their observed energy at earth, $E_{obs} = \frac{E_R}{1+z}$.

The absorption probability at $z = 0$ is just the few percent result presented earlier for a non-evolving Universe. From there, the absorption probability increases dramatically with increasing z because the $C\nu B$ density increases with z as $(1 + z)^3$. The obvious lesson from Fig. (4) is that neutrinos emitted by distant sources with significant redshifts z_{source} should show considerable absorption, especially in the energy-bin at $E_{obs} \sim \frac{E_R}{1+z_{source}}$. If a sufficient data set of EECR neutrinos can be collected with future experiments, these absorptions dips may be visible. According to formula (12), identification of the energy of the dips directly enables neutrino mass-spectroscopy!

4. Resonant Emission: Z-bursts

Let us call the distance over which a stable particle can propagate without losing more than an order of magnitude of its energy the GZK distance, $D_{\rm GZK}$. For a photon it is of order 10 Mpc at 10^{20} eV, rising to $\mathcal{O}(100)$ Mpc or more at 10^{22} eV, with the exact numbers depending on the strengths of the diffuse radio background. For a proton it is $D_{\rm GZK} \sim 50$ to 100 Mpc. For a neutrino, it exceeds the Hubble-size of the Universe, as we have seen. Primary neutrinos which annihilate with relic neutrinos within the GZK zone ($D < D_{\rm GZK}$) create a "local" flux of EECR nucleons and photons.

For each 50 Mpc of travel through the mean neutrino density, the probability for a neutrino with resonant energy to annihilate to a Z–boson is 3.6×10^{-4}. Since the branching fraction for a Z to decay to hadrons is 70%, one part in 4000 of the resonant neutrino flux will be converted into a "Z–burst" containing ~ 20 extreme-energy photons and ~ 2 extreme-energy nucleons within $D_{\rm GZK} \sim 50$ Mpc of earth in this homogeneous, zero chemical potential neutrino universe. These photons and nucleons are in principle observable at earth. A drawing of Z-burst production within the $D_{\rm GZK}$ distance of earth is shown in Figure (4).

4.1. Rate Enhancement from Neutrino Clustering

We live in a matter–rich portion of the Universe. The Supergalactic Cluster, the Local Group, and the Galactic Halo each provides a "local potential well" which is expected to trap neutrinos and enhance the local relic–neutrino density compared to the universal average. Moreover, any neutrino–antineutrino asymmetry (parameterized by a chemical potential) increases the sum of the neutrino plus antineutrino relic densities. Therefore, the value of 0.025% for the probability of a resonant neutrino creating a Z–burst within the 50 Mpc GZK zone, obtained without neutrino clustering or asymmetry, is the absolute minimum for the local annihilation probability in a Big Bang Universe. With clustering and/or asymmetry, the probability will be larger.

Let us define some fiducial values for cluster sizes (L_s) and the mean separation distance of the clusters (L_{ss}). We take $D_S = 20$ Mpc for the diameter of the Virgo Supercluster, the only supercluster well within our GZK zone, and 100 Mpc, typical of the distance across a cosmic void, for the supercluster mean separation distance D_{SS}. We take $D_C = 5$ Mpc for the typical diameter of galactic clusters and $D_{CC} = 50$ Mpc as the typical distance between neighboring galactic clusters. For our Local Group of ~ 20 galaxies, we take $D_{Gp} = 2$ Mpc, and $D_{Gp-Gp} = 20$ Mpc for the mean separation distance between groups. $D_G = 50$ kpc is a typical diameter of

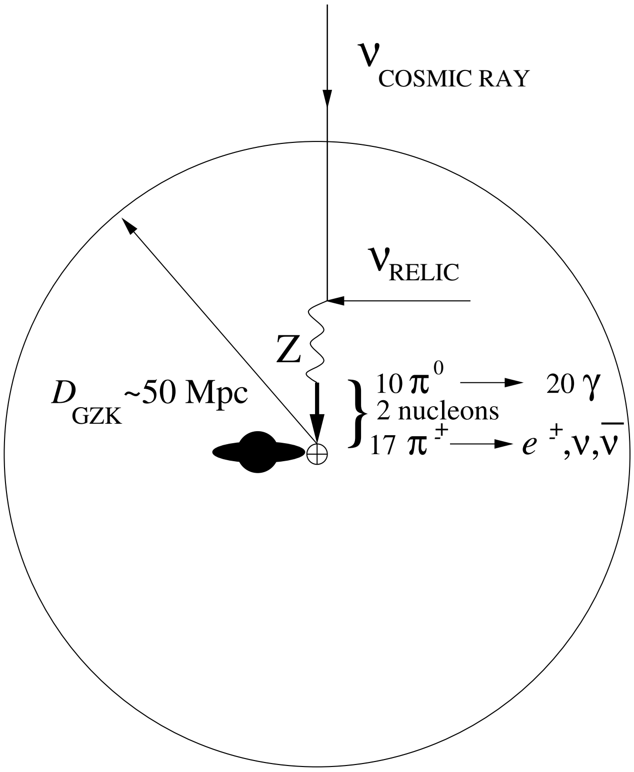

Figure 4: Schematic diagram showing the production of a Z–burst resulting from the resonant annihilation of a cosmic–ray neutrino on a relic (anti)neutrino. If the Z–burst occurs within the GZK zone ($\sim$ 50 to 100 Mpc) and is directed towards the earth, then photons and nucleons with energy above the GZK cutoff may arrive at earth and initiate super–GZK air–showers.

galactic halos (including our own) and $D_{GG} = 1$ Mpc is a typical distance between neighboring galaxies. With these fiducial values for sizes and separation distances, the respective density enhancements $(L_{ss}/L_s)^3$ are of order 100, 10^3, 10^3, and 10^4, for the Supercluster, Cluster, Local Group, and Galactic halo. Such would be the clustering for neutrinos if they were as efficient as baryons for clustering on these scales.

The geometrical scaling law that governs the increase in annihilation rate when neutrinos are clustered rather than distributed uniformly throughout the Universe is $(L_{ss}/L_s)^3(L_s/D_H) = L_{ss}^3/L_s^2 D_H$. If the neutrino clustering scale L_s is less than the GZK distance of 50 to 100 Mpc, then the Z–burst production probability within the GZK zone also scales with this factor, yielding $(L_{ss}^3/D_H\, L_s^2)(3.0\, h_{65}^{-1}\,\%)$. Including the 70% hadronic branching ratio of the Z, one then gets the probabilities 1.3%, 2.4%, 1.0%, and 0.2% (independent of h_{65}), for Z–burst production by a neutrino of at resonant energy traversing the Supercluster, Cluster, Local Group, and Galactic halo, respectively. The larger clusters all give a robust probability, within a factor of two of each other, and of order of a per cent. Since neutrino clustering is not so efficient (as discussed in §(), the 1% probability for cosmic ray neutrinos at their resonant energy to annihilate within the $\sim$ 50 Mpc zone of earth is perhaps an overly-optimistic but nevertheless encouraging upper limit.

It has been pointed out[11)] that local neutrino clustering is not only helpful to the Z-burst model, but may be required in order to de-weight the effect of distant Z-bursts electromagnetically cascading to a density of 30 MeV to 100 GeV photons in excess of the EGRET experimental bound[12)]. However, recent work[13)] challenges this claim.

Rate enhancement also occurs if there is a ν-$\bar{\nu}$ asymmetry in the $C\nu B$, for this necessarily increases the $C\nu B$ density, as discussed in §(1.2).

4.2. Does Nature Provide?

Two gifts from Nature are required to produce measurable Z-burst rates. The first is a significant neutrino flux at $\gtrsim 10^{21}$ eV, and the second is a neutrino mass in the 0.1 to 1 eV range. If these gifts are provided, then Z-bursts are an inevitable consequence of the SM of particle physics, and the Standard Cosmological model (hot Big-Bang). Does Nature provide neutrino mass and flux?

The existence of neutrino mass in the desired range seems nearly guaranteed from the tritium decay upper bound[14)] and the lower bounds inferred from the terrestrial neutrino oscillation experiments. The simplest explanation for the atmospheric neutrino results is neutrino oscillations driven by a mass–squared difference of $\delta m^2_{\rm atm} \sim 3 \times 10^{-3}{\rm eV}^2$, which implies a neutrino mass of *at least* 0.05 eV. Also, the recent LSND measurement appears to indicate a mass–squared difference $\delta m^2_{\rm LSND} \gtrsim 0.2{\rm eV}^2$ from which one deduces a neutrino mass of at least 0.5 eV. From these lower bounds on neutrino mass, one gets upper bounds on the Z–burst energy of 10^{23} and 10^{22} eV, respectively, just right for extending the air-shower spectrum an order of magnitude or two beyond the GZK cutoff!

Big Bang cosmology places an upper bound on neutrino mass. The fraction of closure density provided by the masses of nonrelativistic neutrinos is $\Omega_\nu = 0.025\, h_{65}^{-2} \sum_j (m_{\nu_j}/\mathrm{eV})$. One sees that eV neutrino masses are required if neutrino hot dark matter is to contribute in any significant way to the evolution of large–scale structure. Studies of structure formation suggest that $\Omega_\nu \lesssim 0.15$, in which case no single neutrino mass may exceed ~ 6 eV.

Better upper bounds on the neutrino masses in the few eV range are available from tritium decay experiments and from large–scale structure formation studies. In addition, the non-observation of neutrinoless double-beta decay provides the further upper bound $|\sum_j U_{ej}^2 m_j| < 0.2$ eV for Majorana neutrino masses. This bound is restrictive in particular models where the complex mixing elements U_{ej} are known. Since cancellations may occur in the sum due to complex phases, and since $|U_{e3}|^2$ is known to be small, the $0\nu\beta\beta$-bound is compatible with large neutrino masses. The challenging issue of how experiments might actually determine the absolute neutrino mass is discussed by Paes and Weiler[15)].

So it appears that Nature has provided one or more neutrino masses in the optimal range for producing energetic Z-bursts which result in air-showers just above E_{GZK}. When resonant annihilation to produce Z's was first proposed,[5)] it was not known that neutrinos had a mass, let alone an optimal mass.

A considerable cosmic neutrino flux above E_{GZK} is required for the Z–burst hypothesis to successfully explain the super–GZK events. The requirement is that the product of the resonant energy times the neutrino flux per flavor at the resonant energy, times the annihilation probability within the GZK zone (0.025% without neutrino clustering and up to 1% with neutrino clustering), times the photon and nucleon multiplicity per burst (~ 20), is comparable to the observed flux at 10^{20} eV. The resulting requirement on the neutrino flux is roughly $E_R\, F_{\nu_j}(E_R) \sim 10^{-18.5\pm1}/\mathrm{cm}^2/\mathrm{s}/\mathrm{sr}$. Such a neutrino flux at $E \sim 10^{22}$ eV is directly measurable in a teraton (10^{12} ton) detector like EUSO[16)] and OWL[17)], and possibly in a search for radio pulses produced by high energy neutrinos penetrating a small column–density of matter in the limb of the moon[18)].

While certainly large, this required neutrino flux violates no existing limits.[d] However, this large neutrino flux at extreme-energies probably requires unusual source

[d]Existing limits bound the product of the unknown ν-N cross-section times the flux at extreme-energy. It was recently shown[19)] that the commonly-used cross-section extrapolations violate perturbative unitarity above $E \sim 10^{17.5}$ eV. At $E = 10^{20}$ eV, the SM cross-section must be at least an order of magnitude below the extrapolations. The net result of this is that neutrino flux bounds at extreme-energy are correspondingly weakened.

dynamics[20].

5. Might Z-bursts Explain the Super-GZK Events?

An unsolved astrophysical mystery, now forty years old, is the origin and nature of the EECRs responsible for the observed air-shower events at highest energies, $\sim 10^{20}$ eV. To date, twenty–four air–shower events with energies near and above 10^{20} eV have been observed by the Volcano Ranch, Haverah Park, Yakutsk, Fly's Eye, Akeno/AGASA, and most recently, HiRes collaborations[21]. The origin of these events is a mystery, for there are no visible source candidates within 50 Mpc except possibly M87, a radio-loud AGN at $\sim$ 20 Mpc, and Cen-A (NGC5128), a radio galaxy at 3.4 Mpc, and neither of these is in the direction of any of the observed events[22]. Since the observed events display a large-scale isotropy, many sources rather than one source seem to be required. The nature of the primary particle is also mysterious, because interactions with the 2.73K CMB renders the Universe opaque to nucleons above $E_{\rm GZK} \sim 5 \times 10^{19}$ eV, and double pair production on the cosmic radio background renders the Universe opaque to photons at even lower energies. The theoretical prediction of the end of transparency for nucleons at $E_{\rm GZK}$ is the famous "GZK cutoff" [23]. Figure (5) shows a recent compilation of the AGASA data set, clearly extending beyond $E_{\rm GZK}$. It is now clear that the EECR spectrum extends beyond the GZK cutoff, seriously challenging theory.

The origin of this Greisen–Kuzmin–Zatsepin (GZK) cutoff[23] is the degradation of the proton energy by the resonant scattering process $p + \gamma_{2.7K} \rightarrow \Delta^* \rightarrow N + \pi$ when the proton is above the resonant threshold for Δ^* production; $\gamma_{2.7K}$ denotes a photon in the $2.7K$ cosmic background radiation. A proton produced at its cosmic source at a distance D from earth with an initial energy E_p well above $E_{\rm GZK}$ will on average lose 20% of its energy per interaction length of 6 Mpc to arrive at earth with only a fraction $\sim (0.8)^{D/6\,{\rm Mpc}}$ of its original energy. Therefore, proton energy is not lost significantly only if the highest–energy protons come from relatively nearby sources, $\lesssim$ 50 to 100 Mpc.

The long-standing theory challenges in attempting to understand the super-GZK data are: (i) What cosmic source could produced primary particles at such extremely high energies? and (ii) If the sources are distant ($\gtrsim$ 100 Mpc), then how could these primaries have propagated through the cosmic background radiation without substantial energy loss? The acceleration mechanism either requires a Zevatron[25] accelerator ($1ZeV \equiv 10^{21}$ eV), distant because such a source could not be missed if it were nearby; or speculative decaying super-massive particles[26] (SMPs) or topological defects[27] (TDs) with mass-scale $\gtrsim 10^{22}$ eV, clustered nearby; or possibly magnetic monopoles[28] accelerated by the cosmic magnetic fields. From distant Zevatrons, only neutrinos among the known particles can propagate unimpeded to earth.

Adding to the drama and mystery at present is the observed **large-scale isotropy**

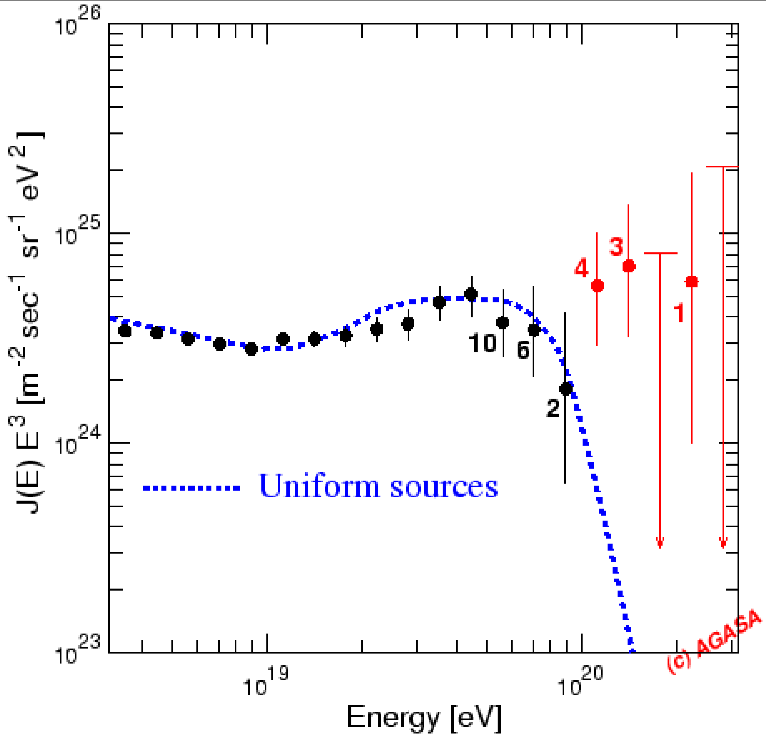

Figure 5: Extreme-energy cosmic ray spectrum as observed by AGASA. Error bars are 68% C.Limits and numbers denote events per energy bin. The dashed line is the spectrum expected from uniformly-distributed astrophysical sources (from the AKENO website[24)]).

and **small-scale anisotropy**. Surely these characteristics hint at a solution to the mystery of origin; protons, nuclei, and magnetic charges bend in cosmic magnetic fields, whereas photons and neutrinos do not.

With more data above $E_{\rm GZK}$, several distinct telltale signatures including the isotropy/anisotropy-scales will allow one to discriminate among the many models proposed for the origin and nature of the EECRs. The various models and the signatures that distinguish these models are reviewed recently by Weiler[29)]. A leading candidate to explain the occurrence of the super-GZK events is the Z-burst model.

5.1. The Significance of Pairs and Triplets in the EECR Angular Distribution

The AGASA experiment has presented data strongly suggesting that directional pairing of events on the celestial sky (with arrival times displaced by only ~ 2 to 3 years) is occurring at higher than chance coincidence[30)]. Of the 47 published AGASA events above 4×10^{19} eV, 9 are contained in three doublets and one triplet with separation angle less than the angular resolution of 2.5°. The chance probability of this clustering occurring in an isotropic distribution is less than 1%. The chance probability for the triplet alone is only 5%. Of the seven events above 10^{20} eV, three are counted among the doublet events. Most recently, AGASA has reported two more events above $E_{\rm GZK}$[31)]. Each aligns in direction with a previous event, reducing further the probability for random clustering to 0.07% at 3σ. Comparisons of event directions in a combined data sample of four experiments further supports non-chance coincidences, especially in the direction of the SuperGlactic Plane[32)]. A very recent analysis[33)] of the AGASA and Yakutsk data in terms of two-point angular correlation functions finds the probability of the observed clustering being due to chance is 4×10^{-6}.

Such event–pairing argues for a common source of some duration, emitting stable neutral primaries having a small magnetic moment. The stability requirement is that $c\tau$ exceed $D \sim D_H$. The resulting limit on the rest frame lifetime is then $\tau_{\rm RF} \gtrsim (m/E_{\rm GZK})(D_H/c) = 10^{-2}(m/{\rm eV})h_{65}^{-1}s$; for a GeV primary, this is about one year. The requirement that the primary be neutral is necessary to allow straight trajectories for the paired primaries as they travel through the (probably nanogauss or greater) extragalactic magnetic fields. The requirement that the primary have a small magnetic moment is necessary to avoid significant energy losses via magnetic dipole interactions with the ambient 2.7K microwave background. Neutrino primaries satisfy these three criteria.

Neutrinos as primaries presents an immediate obstacle: the SM event rate for a neutrino-induced air-shower is down from that of an electromagnetic or hadronic interaction by six orders of magnitude. In particular, the famous Fly's Eye event at 3×10^{20} eV occurred high in the atmosphere, whereas neutrino interactions are expected to occur at low altitudes where the air is dense. The Z-burst hypothesis circumvents this difficulty by providing photons and nucleons as the particles initiating air-showers.[e]

If neutrinos are the primaries, they should point back to their sources, thereby enabling point-source astronomy for the most energetic sources in the Universe. It was reported[34)] that five events at 10^{20} eV did in fact point toward extragalactic compact radio-loud quasars, just the class of objects which could accelerate EECRs to ZeV energies via shock mechanisms. With the inclusion of subsequent data, this association is controversial[35)]. Most recently, BL-Lac objects (believed to AGNs with a jet pointing directly toward the earth) have been found to correlate with the directions of the most energetic AGASA and Yakutsk events[36)]. Correlation at 2.5° with a chance probability of 2×10^{-5} and again at $\sim 10°$ with a chance probability 3×10^{-4} were found. A natural interpretation is that it is Z-bursts that are pointing to the BL-Lac's, with the "local" photons and nucleons from the burst providing the angular correlations. It will be very interesting to learn in the near future whether the paired-event showers are initiated by photons or nucleons.

5.2. The Z-burst Hypothesis

The hypothesis of the Z-burst model[6,7)] is that the primary particles which propagate across cosmic distances above the GZK cutoff energy are neutrinos, which then annihilate with the $C\nu B$ within the GZK zone ($D < D_{\rm GZK} \sim 50$ Mpc) to create a "local" flux of nucleons and photons above $E_{\rm GZK}$, as shown in Fig. (). Since a resonant cosmic-ray neutrino arriving at earth from a cosmically distant source has an annihilation probability on the $C\nu B$ of roughly $3.0\, h_{65}^{-1}$ % [5)], the probability for a resonant neutrino to annihilate to a Z-burst within distance $D_{\rm GZK}$ is then 2.5×10^{-4} for a homogeneous $C\nu B$[6)]. The local annihilation rate is enhanced if our matter-rich portion of the Universe clusters neutrinos[6,7)], or if there is an intrinsic CP-violating ν-$\bar{\nu}$ asymmetry[37)]. If the Z–burst points in the direction of earth and occurs within the GZK distance, then one or more of the photons and nucleons in the burst may initiate a super–GZK air–shower at earth[6,7)]. For a sufficient cosmic neutrino flux, the hypothesis successfully explains the observed air–showers above $E_{\rm GZK}$.

It has been noted in[37)] that a degeneracy parameter of $\xi \sim 5$ (giving a neutrino asymmetry factor of ~ 4) effects an enhancement in the neutrino or antineutrino number density of ~ 30, thereby decreasing the resonant annihilation mfp for antineutrinos or neutrinos to $\sim D_H$ and maximizing the Z–burst probability within the GZK zone to $\frac{1}{2} \times \frac{1}{e}\frac{D_{\rm GZK}}{D_H} \sim 0.2\, h_{65}\%$. With neutrino clustering in addition to the asymmetry discussed here, this probability is larger still. The factor of $\frac{1}{2}$ in the probability reflects the fact that with a large asymmetry, one of n_ν or $n_{\bar{\nu}}$ is enhanced but the other is driven near zero. Consequently, the annihilation probability for the cosmic–ray $\bar{\nu}$ or ν, respectively, is negligible.

[e] Another approach is to postulate that the neutrino cross-section becomes strong at 10^{20} eV.

If there is a net neutrino number enhancement of ~ 30, then the cosmological bound $\Omega_\nu \lesssim 0.15$ requires that $m_\nu \lesssim 0.4$ eV for the enhanced species. This in turn puts a lower bound on the resonant energy of $E_R \gtrsim 10^{22}$ eV.

According to eqn. (**??**), an upper bound on the neutrino mass of 4 eV implies that no Z–burst energy will fall below 10^{21} eV. This is a comfortable factor of 20 or so above the GZK cutoff. From the lower bounds on neutrino mass deduced from the SuperK and LSND experiments, one gets upper bounds on the Z–burst energy of 10^{23} and 10^{22} eV, respectively. It is uncanny that the allowed range for Z–burst energies of 10^{21} to 10^{23} eV, deduced from cosmology, tritium decay, and oscillation experiments, is just right for extending the air-shower spectrum an order of magnitude or two above the GZK cutoff!

The Z-burst model seems to predict a preponderance of photon primaries relative to nucleon primaries. From the experimental side, the longitudinal profile of the world's highest-energy event, the Fly's Eye event at 3×10^{20} eV, favors a nucleon primary over a photon primary. The new HiRes experiment will be able to reconstruct longitudinal profiles from atmospheric N_2-fluorescence, as the Fly's Eye experiment did. Data from this new experiment should be definitive as to the nature of the primary composition.

Without simulation and modeling it is not clear what ratio of photon to nucleon initiated air–showers is to be expected from Z-bursts. The *a priori* photon–to–nucleon ratio in the Z-burst is about 10. However, the hardness of the nucleon spectrum compared to the photon spectrum as measured in Z–decay mitigates this ratio if a selection is made for the very highest energy particles. The mean pion energy from Z decay is about a third of the mean nucleon energy[38)]. The mean photon energy from π^0–decay is half again that of the pion. Complicating the prediction for the photon to proton ratio for air–shower initiation is the different physics underlying the attenuation of photons on the radio background, and degradation of the proton energy on the 2.7K microwave background. Also, the development of photon–initiated air–showers above $E_{\rm GZK}$ is skewed by the coherent electromagnetic "LPM" effect and by high–altitude photon–absorption on the earth's magnetic field, either of which may affect the shower identification and interpretation. Finally, the average values for the multiplicities and energies presented here must be used with some caution, since fluctuations in multiplicity and particle-types per event, and in energy per individual particle, are large. For example, although the mean number of baryon–antibaryon pairs per hadronic Z–decay is one, the probabilities for 0, 1, 2, 3, and 4 pairs are 37%, 37%, 18%, 6%, and 1.5%, respectively, if the number of pairs is governed by Poisson statistics. What does seem clear is that there should be a dominant fraction of photon–initiated air–showers not far below the upper end of the observed spectrum.

Some numerical simulations of the Z–burst hypothesis have been performed. The conclusion of Yoshida et al.[11)] is that the fractions of photon and nucleon primaries are similar above 10^{20} eV, with photons dominating below 10^{20} eV. They further conclude that one needs a healthy clustering of $C\nu B$ neutrinos of $\sim$ eV mass on the Supercluster scale to produce the events and rate observed above the GZK cutoff without violating lower energy flux limits. The simulation of Gelmini[39] shows a good fit to the data with nucleons dominating photons below 10^{20} eV, and vice versa above 10^{20} eV. The very recent conclusion of Fodor et al.[13] is that the super-GZK data is well fit with Z-burst nucleons, with the photons being harmlessly absorbed on the radio background; no local $C\nu B$ overdensity required. These authors give fits for the $C\nu B$ mass responsible for the bursts: $m_\nu = 2.34^{+1.29}_{-0.84}$ eV for their "Galactic halo power-law spectrum" and $0.26^{+0.20}_{-0.14}$ eV for their "extragalactic power-law spectrum."

These simulations do not all agree with one another in details, but they all agree that Z-bursts may be a viable explanation for the 35 year old question: What is the origin of the air-shower events observed above $E_{\rm GZK}$.

6. Summary and Prospects

Resonant neutrino annihilation provides the best hope at present to actually measure the relic $C\nu B$. The inferred neutrino mass values from atmospheric and terrestrial neurtino experiments suggest that annihilation dips and emission Z-bursts are plausible phenomena just above $E_{\rm GZK}$. Furthermore, the existence of EECR events above $E_{\rm GZK}$ suggests that Z-bursts may have already been observed. If the Z-burst hypothesis is correct, then air-shower observations have already shown the existence of the relic-neutrino gas liberated from the primordial early-Universe plasma when the Universe was only one second old.

Clearly, we live in exciting EECR times, and we possess the technology to prove this is so. The super-GZK events provide ample motivation to build the next generation of CR detectors, Auger and Telescope Array (TA), and to plan even farther beyond for a teraton detector like EUSO, OWL and AirWatch. At 10^{20} eV, AGASA provides about an event per year, and HiRes about an event per month. Auger and TA will see two such events per week, while EUSO and OWL have the potential to collect such an event every two hours. As the data sample grows, statistical studies will validate or invalidate the Z-burst (and other) model(s).

Possible signatures to validate or invalidate the Z–burst hypothesis presented here will be forthcoming. Signatures are abundant. The most striking of these are:
(i) a new cutoff energy at $E_R = 4\ ({\rm eV}/m_\nu) \times 10^{21}$ eV;
(ii) a large γ/p ratio for primaries near the upper end of the observable cosmic–ray spectrum;
(iii) pairing of events in direction, and directional pointing of shower–axes to their cosmic sources; and
(iv) a neutrino flux sufficiently large above the GZK cutoff energy that direct measurement is possible with the proposed Auger, Telescope Array, and OWL/AirWatch

detectors.

7. Acknowledgements

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