THE ASTROPHYSICAL JOURNAL, 517:725–733, 1999 June 1

ULTRA–HIGH-ENERGY NEUTRINO SCATTERING ONTO RELIC LIGHT NEUTRINOS IN THE GALACTIC HALO AS A POSSIBLE SOURCE OF THE HIGHEST ENERGY EXTRAGALACTIC COSMIC RAYS

D. FARGION,[1,2] B. MELE,[1] AND A. SALIS

Dipartimento di Fisica, Universitá degli Studi di Roma "La Sapienza," Piazzale Aldo Moro 2, 00185 Roma, Italy; Daniele.Fargion@roma1.infn.it

Received 1997 October 9; accepted 1999 January 4

ABSTRACT

Diffuse relic neutrinos with light mass are transparent to ultra–high-energy (UHE) neutrinos at thousands of EeV, which are born through the photoproduction of pions by UHE protons on relic 2.73 K blackbody radiation (BBR), and originate in active galactic nuclei (AGNs) at cosmic distances. However, these UHE ν's may interact with others (mainly the heaviest: ν_{μ_r}, ν_{τ_r}, and respective antineutrinos) that are clustered into hot dark matter (HDM) galactic halos. UHE photons or protons, secondaries of ν-ν_r scattering, might be the final observed signatures of such high-energy chain reactions, and may be responsible for the highest energy extragalactic cosmic-ray (CR) events. Here we consider the conversion efficiency, ramifications, and energetics of these chain reactions for the 1991 October CR event at 320 EeV observed by the Fly's Eye detector in Utah. These quantities seem to be compatible with the distance, direction, and power (observed at MeV gamma energies) of the Seyfert galaxy MCG 8-11-11. The ν-ν_r interaction probability is favored by at least 3 orders of magnitude over a direct ν scattering onto Earth's atmosphere. Therefore, it may better explain the extragalactic origin of the puzzling 320 EeV event, while offering indirect evidence of a hot dark Galactic halo of light neutrinos (i.e., $m_\nu \sim$ tens of eV), probably of τ flavor.

Subject headings: cosmic rays — elementary particles — galaxies: individual (MCG 8-11-11) — Galaxy: halo — scattering

1. INTRODUCTION

The highest energy cosmic rays (CRs), with $E > 10^{19}$ eV (excluding neutrinos), are severely bounded to nearby cosmic distances by the opacity of the 2.73 K blackbody radiation (BBR)(GZK cutoff; see Greisen 1966; Zat'sepin & Kuz'min 1966; Gould & Schreder 1966), as well as by the extragalactic radio background opacity (Clark, Brown, & Alexander 1970; Protheroe & Biermann 1996). The inverse Compton scattering ($e^{\pm}\gamma_{\rm BBR} \to e^{\pm}\gamma$, $p\gamma_{\rm BBR} \to p\gamma$; Longair 1994; Fargion, Konoplich, & Salis 1997; Fargion & Salis 1998), the photopair production at higher energies ($p\gamma_{\rm BBR} \to pe^+e^-$, $\gamma\gamma_{\rm BBR} \to e^+e^-$), and, most importantly, the photoproduction of pions ($p\gamma_{\rm BBR} \to p + N\pi$, $n\gamma_{\rm BBR} \to n + N\pi$, ...; Longair 1994) constrain a 100 EeV CR to a few Mpc for the characteristic path lengths of either charged CRs (protons, nuclei), or neutrons and photons. The most energetic CR event, at 320 EeV, observed by the Utah Fly's Eye detector, keeps the primeval source direction to within few degrees even if the source was a charged one, because of its high magnetic rigidity (Bird et al. 1994). However, no nearby (<60 Mpc) source candidate (AGN or QSO) has been found up to now in the arrival-direction error box. Therefore, at present there is no reasonable explanation for the 320 EeV event if its origin is extragalactic. An alternative solution to this puzzle, based on an extraordinary extragalactic magnetic field (whose coherence length, ranging on the largest astrophysical distances, might be able to bend the CR trajectory from off-axis nearby potential sources, such as M82 and Virgo A [see Elbert & Sommers 1995]) is improbable (Medina-Tanco 1997). The option of a *local* (Galactic halo) origin of the cosmic ray (Fargion & Salis 1995) is unpopular because of the lack of known processes that might be able to accelerate cosmic rays in small Galactic objects such as supernova (SN) remnants or jets up to such high energies. Direct cosmic neutrinos reaching the Earth's atmosphere, while they are able to reach the Earth from any cosmological distance, are unable to produce the shower seen in the 320 EeV event (Elbert & Sommers 1995). Exotic sources for the EeV CR, such as monopole decay or topological defect annihilation, have also been considered (Elbert & Sommers 1995). However, such models do not provide any detailed predictions (because, for example, no one knows the primordial monopole's density), and they seem to be just a posteriori, ad hoc solutions. Here we address a more conventional solution, based on the widely accepted assumption that neutrinos have a light mass and therefore could cluster in large galactic halos, where they might play an important role as *hot dark matter*. Their number density, cross sections, and halo sizes are large enough to produce, by ν-ν electroweak $W^{\pm}/Z$-boson exchange, secondaries inside the galactic halo, mainly photons by π^o decay (Fargion & Salis 1997) and protons, which could be the source of the observed 320 EeV event.

2. RELIC NEUTRINO CLUSTERING

Let us consider the UHE ν scattering onto light relic ν's in the Galactic halo. In principle, any neutrino flavor may be involved as either a source or a target for the present process. Let us label the hitting high-energy neutrino ν and the target relic neutrino ν_r. UHE electronic neutrinos may derive from neutron decay in flight, or at lower energies from muon decay. Muonic neutrinos may be born as secondaries in pion decay. Tau neutrinos may occur if the

[1] Istituto Nazionale di Fisica Nucleare, Roma 1, Italy.

[2] Technion Institute, Engineering Faculty, Haifa, Israel.

primary cosmic rays are generated in hadronic interactions (Dar & Laor 1996), or if some neutrino flavor mixing occurs (Fargion 1997). The target neutrinos, relics of the early universe, are clustered around the Galactic halo. All the neutrino flavors are born at nearly the same cosmic homogeneous BBR density $n_\nu \sim (4/11)n_\gamma$. Neutrinos with a light mass (a few or tens of eV) must condense around galactic halos as a result of their earliest decoupling from thermal equilibrium, and because of the mutual baryon-neutrino multifluid gravitational clustering during galaxy formation (Zeldovich et al. 1980; Fargion 1983). Because of the role neutrino mass plays in defining the early Jeans instability, the free-streaming mass, and the halo size, the heavier (τ or μ) neutrino halos are expected to be more clustered and denser than a lighter (electronic) halo.

Let us review in more detail the role and origin of such hot dark matter (HDM) neutrinos in galactic halos and their role in interactions with UHE neutrinos. In the early universe, thermal equilibrium provides the most efficient source of the present neutrino density, whose relic number can be easily derived by entropy conservation. The MeV neutrino relics decouple from the thermal bath of photons during the first second of the universe's life, as soon as electron pairs (which play the role of catalysts for the neutrino equilibrium) annihilate and heat the relic photons' temperature by an extra factor $(11/4)^{1/3}$ with respect to the neutrino temperature. The cosmological neutrino density for each flavor and state stems directly from the previous factor, and becomes $n_\nu = (4/11)n_\gamma \simeq 108\ \mathrm{cm}^{-3}$. Charged currents keep the electronic neutrinos in thermal equilibrium, while the μ and τ neutrinos are kept in equilibrium by the slightly less efficient neutral currents. The cosmic expansion *cools* the ultrarelativistic neutrino, and as soon as it reaches the nonrelativistic regime ($\kappa_B T_\nu \simeq m_\nu c^2$) allows the collisionless neutrino fluid to increase its density contrast (Fargion 1983). The baryon density perturbations are meanwhile smeared out by photons up to the Silk size and mass at a later recombination epoch ($z \sim 1500$). Once the baryons decouple from radiation, their density contrast $\delta\rho_B/\rho_B$ may grow around the primordial neutrino gravitational seeds. Moreover, the baryons may dissipate their gravitational energy (by radiation), leading to faster nonlinear gravitational galaxy formation. At this stage, the massive neutrinos are drawn into a sink by the baryonic galactic growing (gravitational) potential, and they finally fill up an extended hot dark galactic halo, i.e., a HDM halo. We apply a simple adiabatic approximation to evaluate the present neutrino number density in those halos (Fargion et al. 1995, 1996). We find that the final neutrino number density in the galactic halo, n_{ν_r}, is enhanced by a factor of $\rho_{GB}/\rho_B \sim 10^5$–$10^7$, where ρ_{GB} and ρ_B are the present baryonic mass densities in inhomogeneous galaxies and in the average cosmic media, respectively. In the present work we assume $n_{\nu_r} = 10^{7-9}\ \mathrm{cm}^{-3}$. The uncertainty window of 2 orders of magnitude arises from our ignorance of the exact cosmic baryon density and galactic (luminous and dark) mass density, as well as of the neutrino baryon clustering efficiency. The resulting extended neutrino halo, related to the combined free-streaming length and the characteristic Jeans wavelength of the two fluids (Fargion 1983), is $l_g \simeq 300$ Kpc $\sim 10^{24}$ cm. The characteristic mass density needed to solve the Galactic dark matter problem is $\rho_{oc} \sim 0.3$ GeV cm^{-3} (Fargion et al. 1995). The corresponding allowed mass density for the relic neutrino halo for the two extreme clustered value we assumed above is $\rho(r)_{o\nu} \sim 0.1/[1 + (r/a)^2](m_\nu/10\ \mathrm{eV}) \times 10^{0-2}\ \mathrm{GeV\ cm^{-3}}$, where $a \sim 10$ Kpc, well within the critical value of ρ_{oc}.

3. NEUTRINO-NEUTRINO INTERACTION

Now let us examine the processes that can occur in the interaction of UHE and relic neutrinos (see also Roulet 1993). The two main channels involve a $W^\pm$ or a Z^o exchange via the reactions $\nu_\mu \nu_{\tau_r} \to \mu\tau$ and $\nu_\mu \nu_{\mu_r} \to$ hadrons, respectively. For a ν-ν_r interaction mediated in the t-channel by the W exchange, the asymptotic cross section reaches a plateau of nearly constant value when $s \to \infty$. On the other hand, for a ν-ν_r interaction mediated in the s-channel by the Z exchange, a peculiar peak in the cross section occurs because of the resonant Z production at $s = M_Z^2$. However, this occurs for a very narrow and fine-tuned window of energy, and for a neutrino mass of $m_\nu \sim 4\ \mathrm{eV}(E_\nu/10^{21}\ \mathrm{eV})^{-1}$. This resonance for massive light cosmological neutrinos is analogous to the well-known resonance in $\nu_e e^- \to W^-$ (Glashow 1960; Berezinsky & Gazirov 1977). We only note this possibility here; we do not assume the lucky coincidence. The exact cross section for the ν_μ-$\bar{\nu}_{\tau_r}$ (and charge-conjugated $\bar{\nu}_\mu$-ν_{τ_r}) interaction via a W exchange in the t-channel, neglecting the neutrino masses, is

$$\sigma_W(s) = \sigma_{\mathrm{asym}} \frac{A(s)}{s} \left(1 + \frac{M_W^2}{s} \times \left\{2 - \frac{s + B(s)}{A(s)} \ln\left[\frac{B(s) + A(s)}{B(s) - A(s)}\right]\right\}\right), \quad (1)$$

where $s^{1/2}$ is the center-of-mass energy, the functions $A(s)$, $B(s)$ are defined as

$$A(s) = \sqrt{[s - (m_\tau + m_\mu)^2][s - (m_\tau - m_\mu)^2]}\ ,$$
$$B(s) = s + 2M_W^2 - m_\tau^2\ , \quad (2)$$

and

$$\sigma_{\mathrm{asym}} = \frac{\pi\alpha^2}{2 \sin^4 \theta_W M_W^2} \simeq 108.5\ \mathrm{pb}\ , \quad (3)$$

where α is the fine-structure constant, θ_W is the Weinberg angle, and σ_{asym} is the asymptotic behavior of the cross section in the ultrarelativistic limit

$$s \simeq 2E_\nu m_\nu = 2 \times 10^{23}\left(\frac{E_\nu}{10^{22}\ \mathrm{eV}}\right)\left(\frac{m_\nu}{10\ \mathrm{eV}}\right) \mathrm{eV}^2 \gg M_W^2\ . \quad (4)$$

On the other hand, the interaction of neutrinos of the same flavor can occur via a Z-exchange in the s-channel (ν_i-$\bar{\nu}_{i_r}$, and charge conjugated). The cross section for hadron production in $\nu_i \bar{\nu}_i \to Z^* \to$ hadrons is

$$\sigma_Z(s) = \frac{8\pi s}{M_Z^2} \frac{\Gamma(Z^o \to \mathrm{invis.})\Gamma(Z^o \to \mathrm{hadr.})}{(s - M_Z^2)^2 + M_Z^2 \Gamma_Z^2}\ , \quad (5)$$

where $\Gamma(Z^o \to \mathrm{invis.}) \simeq 0.5$ GeV, $\Gamma(Z^o \to \mathrm{hadr.}) \simeq 1.74$ GeV, and $\Gamma_Z \simeq 2.49$ GeV are the experimental Z decay width into invisible products, the Z decay width into hadrons, and the Z full decay width (Particle Data Group 1996), respectively.

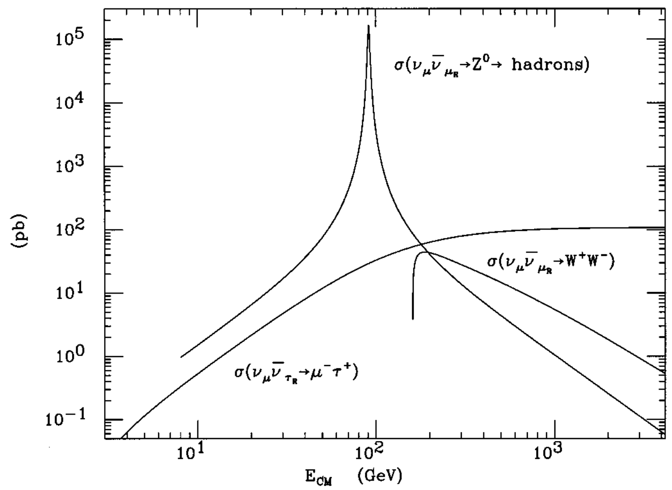

FIG. 1.—Total cross sections for the indicated processes as a function of the center-of-mass energy (for a relic neutrino mass $m_\nu = 10$ eV).

Apart from the narrow Z resonance peak at $s^{1/2} = M_Z$, the asymptotic behavior is proportional to $1/s$ for $s \gg M_Z^2$. For energies of $s^{1/2} > 2M_W$, one must include the additional channel of W pair production, $\nu_i \bar{\nu}_{i_r} \to W^+ W^-$. The corresponding cross section is (Enquist, Kainulainen, & Maalampi 1989)

$$\sigma_{WW}(s) = \sigma_{\rm asym} \frac{\beta_W}{2s} \frac{1}{(s - M_Z^2)} [4L(s)C(s) + D(s)] , \quad (6)$$

where $\beta_W = (1 - 4M_W^2/s)^{1/2}$, and the functions $L(s)$, $C(s)$, and $D(s)$ are defined as

$$L(s) = \frac{M_W^2}{2\beta_W s} \ln\left(\frac{s + \beta_W s - 2M_W^2}{s - \beta_W s - 2M_W^2}\right) ,$$

$$C(s) = s^2 + s(2M_W^2 - M_Z^2) + 2M_W^2(M_Z^2 + M_W^2) , \quad (7)$$

$$D(s) = \frac{1}{12M_W^2(s - M_Z^2)} \times [s^2(M_Z^4 - 60M_W^4 - 4M_Z^2 M_W^2) + 20M_Z^2 M_W^2 s(M_Z^2 + 2M_W^2) - 48M_Z^2 M_W^4(M_Z^2 + M_W^2)] .$$

The asymptotic behavior of this cross section is proportional to $(M_W^2/s)\ln(s/M_W^2)$ for $s \gg M_Z^2$. In Figure 1 we show the three cross section equations (1), (5), and (6) as

TABLE 1

MAIN $W^\pm$ CHANNEL REACTIONS CHAINS (T-CHANNEL) FOR FINAL PHOTON PRODUCTION

Reaction	Probability	Multiplicity	Secondary Energy (eV)
1a:			
$p + \gamma \to (p, n) + 2\pi$	$P_{1a} \simeq 1$	$M_{1a} = 1$[a]	$E_\pi \sim E_p/3$
2a:			
$\pi^+ \to \mu^+ + \nu_\mu$			
$\pi^- \to \mu^- + \bar{\nu}_\mu$	$P_{2a} \simeq 1$	$M_{2a} = 1$	$E_\nu \sim 0.21E_\pi = 7 \times 10^{-2}\ E_p$
2a′:			
$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$			
$\mu^- \to e^- + \bar{\nu}_e + \nu_\mu$	$P_{2a'} \simeq 1$	$M_{2a'} = 1$	$E_\nu \sim E_\mu/3 = 0.26E_\pi = 8.8 \times 10^{-2}\ E_p$
3a:			
$\nu_\mu + \bar{\nu}_{\tau_r} \to \mu^- + \tau^+$			
$\bar{\nu}_\mu + \nu_{\tau_r} \to \mu^+ + \tau^-$	$P_{\nu\nu} = \sigma_{\nu_\mu \bar{\nu}_\tau} n_{\nu_r} l_g \sim 7.5 \times 10^{-4}$–$10^{-2}$	$M_{3a} = 1$	$E_\tau \sim E_{\nu_\mu}/2 = 3.5 \times 10^{-2}\ E_p$
3a′:			
$\nu_\mu + \bar{\nu}_{\tau_r} \to \mu^- + \tau^+$			
$\bar{\nu}_\mu + \nu_{\tau_r} \to \mu^+ + \tau^-$	$P_{\nu\nu} = \sigma_{\nu_\mu \bar{\nu}_\tau} n_{\nu_r} l_g \sim 8 \times 10^{-4}$–$10^{-2}$	$M_{3a} = 1$	$E_\tau \sim E_{\nu_\mu}/2 = 4.39 \times 10^{-2}\ E_p$
4a:			
$\tau^+ \to \pi^o + \bar{\nu}_\tau + X$			
$\tau^- \to \pi^o + \nu_\tau + X$	$P_{4a} \sim 0.37$	$M_{4a} = 1$	$E_{\pi^o} \sim E_\tau/3 = 1.2 \times 10^{-2}\ E_p$
4a′			
$\tau^+ \to \pi^o + \bar{\nu}_\tau + X$			
$\tau^- \to \pi^o + \nu_\tau + X$	$P_{4a'} \sim 0.37$	$M_{4a'} = 1$	$E_{\pi^o} \sim E_\tau/3 = 1.46 \times 10^{-2}\ E_p$
5a:			
$\pi^o \to \gamma + \gamma$	$P_{5a} \sim 1$	$M_{5a} = 2$	$E_\gamma \sim E_{\pi^o}/2 = 5.85 \times 10^{-3}\ E_p$
5a′:			
$\pi^o \to \gamma + \gamma$	$P_{5a'} \sim 1$	$M_{5a'} = 2$	$E_\gamma \sim E_{\pi^o}/2 = 7.3 \times 10^{-3}\ E_p$
Totals:	${}^{a}P^W_{\rm tot} = \Pi_i M_i P_i \sim 5 \times 10^{-4}$–$10^{-2}$		
	${}^{a'}P^W_{\rm tot} = \Pi_i M_i P_i \sim 5.9 \times 10^{-4}$–$10^{-2}$		$E^W_p \sim 4.4 \times 10^{22}$
Additional W channels if there are neutrino $\nu_\tau \leftrightarrow \nu_\mu$ oscillations			
3′a:			
$\bar{\nu}_\tau + \nu_{\tau_r} \to \tau^- + \tau^+$			
$\nu_\tau + \bar{\nu}_{\tau_r} \to \tau^+ + \tau^-$			

NOTE.—In calculating the probability for the ν-ν interaction, we assumed $n_{\nu_R} = 10^{7-9}$ cm^{-3}, $l_g \sim 10^{24}$ cm. The $\sigma_{\nu_\mu \bar{\nu}_\tau}$ value has been obtained from the corresponding cross section and center-of-mass energy in Figure 1.

[a] This multiplicity refers only to charged pions.

TABLE 2

MAIN Z-CHANNEL REACTIONS CHAINS (S-CHANNEL) FOR FINAL PHOTON PRODUCTION

Reaction	Probability	Multiplicity	Secondary Energy (eV)
1b:			
$p + \gamma \rightarrow (p, n) + 12\pi$	$P_{1b} \simeq 1$	$M_{1b} = 6^{a}$	$E_{\pi} \sim E_p/13$
2b:			
$\pi^{+} \rightarrow \mu^{+} + \nu_{\mu}$			
$\pi^{-} \rightarrow \mu^{-} + \bar{\nu}_{\mu}$	$P_{2b} \simeq 1$	$M_{2b} = 1$	$E_{\nu} \sim 0.21 E_{\pi} = 1.6 \times 10^{-2}\ E_p$
2b′:			
$\mu^{+} \rightarrow e^{+} + \nu_e + \bar{\nu}_{\mu}$			
$\mu^{-} \rightarrow e^{-} + \bar{\nu}_e + \nu_{\mu}$	$P_{2b'} \simeq 1$	$M_{2b'} = 1$	$E_{\nu} \sim 0.26 E_{\pi} = 2 \times 10^{-2}\ E_p$
3b:			
$\nu_{\mu} + \bar{\nu}_{\mu_r} \rightarrow Z^{*} \rightarrow 20\pi^{o} + X$......	$P_{\nu\nu} = \sigma_{\nu_{\mu}\bar{\nu}_{\mu}} n_{\nu_r} l_g \sim 10^{-5}$–$10^{-3}$		
$\bar{\nu}_{\mu} + \nu_{\mu_r} \rightarrow Z^{*} \rightarrow 20\pi^{o} + X$......	$P_{3b} \simeq 1$	$M_{3b} = 20$	$E_{\pi^{o}} \sim E_{\nu_{\mu}}/92 = 1.74 \times 10^{-4}\ E_p$
3b′:			
$\nu_{\mu} + \bar{\nu}_{\mu_r} \rightarrow Z^{*} \rightarrow 21\pi^{o} + X$......	$P_{\nu\nu} = \sigma_{\nu_{\mu}\bar{\nu}_{\mu}} n_{\nu_r} l_g \sim 9 \times 10^{-6}$–$10^{-4}$		
$\bar{\nu}_{\mu} + \nu_{\mu_r} \rightarrow Z^{*} \rightarrow 21\pi^{o} + X$......	$P_{3b'} \simeq 1$	$M_{3b'} = 21$	$E_{\pi^{o}} \sim E_{\nu_{\mu}}/95 = 2.1 \times 10^{-4}\ E_p$
4b:			
$\pi^{o} \rightarrow \gamma + \gamma$........................	$P_{4b} \simeq 1$	$M_{4b} = 2$	$E_{\gamma} \sim E_{\pi^{o}}/2 = 8.7 \times 10^{5}\ E_p$
4b′:			
$\pi^{o} \rightarrow \gamma + \gamma$........................	$P_{4b'} \simeq 1$	$M_{4b'} = 2$	$E_{\gamma} \sim E_{\pi^{o}}/2 = 1.05 \times 10^{4}\ E_p$
Totals:	${}^{b}P^{Z}_{\rm tot} = \Pi_i M_i P_i \sim 3.2 \times 10^{-3}$–$10^{-1}$		
	${}^{b'}P^{Z}_{\rm tot} = \Pi_i M_i P_i \sim 3 \times 10^{-3}$–$10^{-1}$		$E^{Z}_{p} \sim 3 \times 10^{24}$

Additional reactions not included in the present analysis

Z channels if there is neutrino flavor mixing $\nu_{\mu} \leftrightarrow \nu_{\tau}$:

3′b

$\bar{\nu}_{\tau} + \nu_{\tau_r} \rightarrow 20\pi^{o} + X$

$\nu_{\tau} + \bar{\nu}_{\tau_r} \rightarrow 20\pi^{o} + X$

Z channel whose efficiency is suppressed by lower ν_e, $\bar{\nu}_e$ energies and n_{ν_e}, $n_{\bar{\nu}_e}$ densities:

3″b:

$\bar{\nu}_e + \nu_{e_r} \rightarrow 20\pi^{o} + X$

NOTE.—In calculating the probability for the ν-ν interaction, we assumed $n_{\nu_r} = 10^{7-9}$ cm^{-3}, $l_g \sim 10^{24}$ cm. The $\sigma_{\nu_{\mu}\bar{\nu}_{\mu}}$ value has been obtained from the corresponding cross section and center-of-mass energy in Figure 1.

[a] This multiplicity refers only to charged pions.

functions of $s^{1/2}$. Of course, in our approach we assume a relic neutrino mass of at least a few eV. Neutrinos that are too light would hardly cluster in the galactic halo. Hence, a suppression factor of 1/2 arises in the cross sections, since in the nonrelativistic rest frame of the gravitationally bounded neutrinos, the helicity of the particle is undefined. This means that the relic neutrino may be found in either left- or right-handed polarization states. Consequently, the interaction may be either left-handed (*active*), or right-handed (*sterile*), leading to the above suppression factor. Majorana neutrinos, which we do not consider here, are insensible to such suppression.

Cosmic distances of $l_c \simeq H^{-1}c \simeq 10^{28}$ cm are transparent to UHE neutrinos even for massive diffused neutrinos (with interaction probability $P_c \simeq \sigma_{\nu\nu_r} n_{\nu} l_c \sim 10^{-4}$). However, denser extended neutrino halos are a more efficient calorimeter. The interaction probability via *W* exchange (*t*-channel) is $P_g \simeq \sigma_{\nu\nu_r} n_{\nu_r} l_g \sim 10^{-3}$–$10^{-1}$, i.e., at least 4 orders of magnitude larger than the corresponding interaction probability of UHE ν's ($E_{\nu} \sim 10^{21}$ eV) in the terrestrial atmosphere ($P_a = \sigma_{\nu\nu} n_{\rm atm} l_{\rm atm} \sim 10^{-5}$; see Gandhi et al. 1996 and references therein), with an additional suppression factor ($\sim 10^{-2}$) due to the high altitude at which the 320 EeV cosmic-ray event took place.

The main reaction chains, from the primary proton down to the final 320 EeV photons or protons, via neutrino-neutrino interactions, are described and summarized in Tables 1, 2, 3, 4, and 5 for the $W^{\pm}$ (*t*-channel), the Z^{o} (*s*-channel), the $\nu\bar{\nu} \rightarrow W^{+}W^{-}$ channel for pion production, and the Z^{o} channel and the $\nu\bar{\nu} \rightarrow W^{+}W^{-}$ channel for proton production, respectively. The final photons are mainly π^{o} decay relics from either the $\tau^{\pm}$, the Z^{o}, or the $W^{\pm}$ secondaries born in ν-ν_r interactions in the Galactic halo. The final protons[3] are among the secondaries of Z^{o} or $W^{\pm}$ hadronic decay.

The columns of the five tables list, respectively: (1) the kind of reaction, (2) the corresponding probability, (3) the resulting averaged multiplicity of the final products, and (4) the secondary averaged energy. We here discuss Table 1 as an example, but the same explanation is also valid for the other tables. In Table 1, reaction 1a shows the photopion production of primary protons of energy E_p onto BBR photons for either a final *p* or *n* creation, plus a couple of π's. The corresponding probability of pion production is practically unity for the cosmic distances we assumed here. The charged pions represent 2/3 of the total number, so we considered a conservative value of 1. Finally, the secondary pion escaping from this reaction has an average energy of 1/3 of the primordial proton energy. In reactions 2a and 2′a, we show the splitting of the chain into two branches as a

[3] We remind the reader that a vector boson hadronic decay generates protons as well as antiprotons. For our purposes the two kind of particles are equally suitable, and we refer to both of them as protons, and we also refer to both hadronic decays, neutrons and antineutrons, under the same proton name.

TABLE 3

MAIN W^+W^- CHANNEL REACTIONS CHAINS FOR FINAL PHOTON PRODUCTION

Reaction	Probability	Multiplicity	Secondary Energy (eV)
1c:			
$p + \gamma \rightarrow (p, n) + 10\pi$	$P_{1c} \simeq 1$	$M_{1c} = 7$[a]	$E_\pi \sim E_p/11$
2c:			
$\pi^+ \rightarrow \mu^+ + \nu_\mu$			
$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$	$P_{2c} \simeq 1$	$M_{2c} = 1$	$E_\nu \sim 0.21 E_\pi = 1.9 \times 10^{-2}\ E_p$
2c′:			
$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$			
$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$	$P_{2c'} \simeq 1$	$M_{2c'} = 1$	$E_\nu \sim 0.26 E_\pi = 2.3 \times 10^{-2}\ E_p$
3c:			
$\nu_\mu + \bar{\nu}_{\mu_r} \rightarrow W^+ + W^-$......			
$\bar{\nu}_\mu + \nu_{\mu_r} \rightarrow W^+ + W^-$......	$P_{\nu\nu} = \sigma_{\nu_\mu \bar{\nu}_\mu} n_{\nu_r} l_g \sim 7 \times 10^{-5}$–$10^{-3}$	$M_{3c} = 2$	$E_W \sim E_{\nu_\mu}/2 = 9.5 \times 10^{-3}\ E_p$
3c′:			
$\nu_\mu + \bar{\nu}_{\mu_r} \rightarrow W^+ + W^-$......			
$\bar{\nu}_\mu + \nu_{\mu_r} \rightarrow W^+ + W^-$......	$P_{\nu\nu} = \sigma_{\nu_\mu \bar{\nu}_\mu} n_{\nu_r} l_g \sim 6 \times 10^{-5}$–$10^{-3}$	$M_{3c'} = 2$	$E_W \sim E_{\nu_\mu}/2 = 1.2 \times 10^{-2}\ E_p$
4c:			
$W^\pm \rightarrow 8\pi^o + X$	$P_{4c} \sim 0.7$	$M_{4c} = 8$	$E_{\pi^o} \sim E_W/33 = 2.9 \times 10^{-4}\ E_p$
4c′:			
$W^\pm \rightarrow 8\pi^o + X$	$P_{4c'} \sim 0.7$	$M_{4c'} = 8$	$E_{\pi^o} \sim E_W/33 = 3.6 \times 10^{-4}\ E_p$
5c:			
$\pi^o \rightarrow \gamma + \gamma$..................	$P_{5c} \simeq 1$	$M_{5c} = 2$	$E_\gamma \sim E_{\pi^o}/2 = 1.45 \times 10^4\ E_p$
5c′:			
$\pi^o \rightarrow \gamma + \gamma$..................	$P_{5c'} \simeq 1$	$M_{5c'} = 2$	$E_\gamma \sim E_{\pi^o}/2 = 1.8 \times 10^4\ E_p$
Totals:	${}^{c}P^{WW}_{\rm tot} = \Pi_i M_i P_i \sim 1.1 \times 10^{-2}$–$10^0$		
	${}^{c'}P^{WW}_{\rm tot} = \Pi_i M_i P_i \sim 9.4 \times 10^{-3}$–$10^{-1}$		$E_p^{WW} \sim 1.8 \times 10^{24}$
Additional reactions not included in the present analysis			
W^+W^- channels if there is neutrino flavor mixing $\nu_\mu \leftrightarrow \nu_\tau$:			
3′c:			
$\bar{\nu}_\tau + \nu_{\tau_r} \rightarrow W^+ + W^-$			
$\nu_\tau + \bar{\nu}_{\tau_r} \rightarrow W^+ + W^-$			
W^+W^- channel whose efficiency is suppressed by lower ν_e, $\bar{\nu}_e$ energies and n_{ν_e}, $n_{\bar{\nu}_e}$ densities:			
3″c:			
$\bar{\nu}_e + \nu_{e_r} \rightarrow W^+ + W^-$			

NOTE.—In calculating the probability for the ν-ν interaction we assumed: $n_{\nu_r} = 10^{7-9}\ {\rm cm}^{-3}$, $l_g \sim 10^{24}$ cm. The $\sigma_{\nu_\mu \bar{\nu}_\mu}$ value has been obtained from the corresponding cross section and center-of-mass energy in Figure 1.

[a] This multiplicity refers only to charged pions.

result of the generation of UHE neutrinos from charged pion decay and secondary muon decay. In reactions 3a and 3a′, we consider the ultrahigh neutrino interaction with the relic cosmic neutrino via the cross section of equation (1), with the relic neutrino number density discussed in the text. The probability takes into account the value of the cross section at the center-of-mass energy involved here for the two neutrinos. In reactions 4a and 4a′, the probability shown refers to the hadronic decay of the τ; as a consequence, the final pion multiplicity is just 1. At the end of the whole chain we calculate the global probability required for the process for both branches, as a product of the multiplicity and the probability that we derived at each step. The initial required proton energy E_p is then derived from the chain, with the requirement that at least one of the two branches could give a photon with the known energy of 320 EeV for the final particle. Tables 2, 3, 4, and 5 should be read in the same way.

4. THE CHAIN REACTIONS LEADING TO THE FINAL PHOTONS

There are at least two main sources of UHE neutrinos: photoproduction of pions by interaction of protons and neutrons on the BBR photons (Longair 1994), and p-p scattering (Dar & Laor 1997). The neutrino UHE secondaries that can survive from cosmic distances up to the neutrino Galactic halo are the first-born muonic and antimuonic from the $\pi^\pm$ decay, and the secondary born from the subsequent $\mu^\pm$ decay.

Let us first consider the three different reaction chains that give rise to final photons. These are (1) the interaction of UHE ν's with relic ν's via $W^\pm$ exchange (t-channel; see Table 1), (2) the Z^o exchange (s-channel; see Table 2), and (3) $\nu\bar{\nu} \rightarrow W^+W^-$ scattering (see Table 3).

All the reactions in Tables 1, 2, and 3 assume an UHE ν born in the photoproduction of pions from primary protons (CR protons) onto BBR photons (through either $p\gamma \rightarrow p + N\pi$ or $p\gamma \rightarrow n + N\pi$, where the pion multiplicity is $N \geq 2$). The primordial proton energy is calibrated according to the final CR photon energy of 320 EeV and the different efficiencies of the chains themselves. In other words, we start with the energy of 320 EeV of the observed particle and walk the chain back from the end to the beginning, according to the chains we have proposed, in order to obtain the fundamental input parameter: the primordial proton energy, which obviously depends on the chain.

TABLE 4

Main Z-Channel Reaction Chains for Final Proton Production

Reaction	Probability	Multiplicity	Secondary Energy (eV)
1d:			
$p + \gamma \rightarrow (p, n) + 9\pi$	$P_{1d} \simeq 1$	$M_{1d} = 6$[a]	$E_\pi \sim E_p/10$
2d:			
$\pi^+ \rightarrow \mu^+ + \nu_\mu$			
$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$	$P_{2d} \simeq 1$	$M_{2d} = 1$	$E_\nu \sim 0.21 E_\pi = 2.110^{-2} E_p$
2d′:			
$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$			
$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$	$P_{2d'} \simeq 1$	$M_{2d'} = 1$	$E_\nu \sim 0.26 E_\pi = 2.6 \times 10^{-2}\ E_p$
3d:			
$\nu_\mu + \bar{\nu}_{\mu_r} \rightarrow Z^* \rightarrow 2p + X$			
$\bar{\nu}_\mu + \nu_{\mu_r} \rightarrow Z^* \rightarrow 2p + X$	$P_{\nu\nu} = \sigma_{\nu_\mu \bar{\nu}_\mu} n_{\nu_r} l_g \sim 2.5 \times 10^{-5}$–$10^{-3}$	$M_{3d} = 2$	$E_p \sim E_{\nu_\mu}/80 \sim 2.6 \times 10^{-4}\ E_p$
3d′:			
$\nu_\mu + \bar{\nu}_{\mu_r} \rightarrow Z^* \rightarrow 2p + X$			
$\bar{\nu}_\mu + \nu_{\mu_r} \rightarrow Z^* \rightarrow 2p + X$	$P_{\nu\nu} = \sigma_{\nu_\mu \bar{\nu}_\mu} n_{\nu_r} l_g \sim 1.8 \times 10^{-4}$–$10^{-3}$	$M_{3d'} = 2$	$E_p \sim E_{\nu_\mu}/83 \sim 3.15 \times 10^{-4}\ E_p$
Totals:	${}^{d}P^Z_{\rm tot} = \Pi_i M_i P_i \sim 3 \times 10^{-4}$–$10^{-2}$		
	${}^{d'}P^Z_{\rm tot} = \Pi_i M_i P_i \sim 2.16 \times 10^{-4}$–$10^{-2}$		$E^Z_p \sim 10^{24}$
Additional reactions not included in the present analysis			
Z-channels if there is neutrino flavor mixing $\nu_\mu \leftrightarrow \nu_\tau$:			
3′d:			
$\bar{\nu}_\tau + \nu_{\tau_r} \rightarrow Z^* \rightarrow 2p + X$			
$\nu_\tau + \bar{\nu}_{\tau_r} \rightarrow Z^* \rightarrow 2p + X$			
Z-channel whose efficiency is suppressed by lower ν_e, $\bar{\nu}_e$ energies and n_{ν_e}, $n_{\bar{\nu}_e}$ densities:			
3″d:			
$\bar{\nu}_e + \nu_{e_r} \rightarrow Z^* \rightarrow 2p + X$			

Note.—In calculating the probability for the ν-ν interaction we assumed: $n_{\nu_r} = 10^{7-9}$ cm^{-3}, $l_g \sim 10^{24}$ cm. The $\sigma_{\nu_\mu \bar{\nu}_\mu}$ value has been obtained from the corresponding cross section and center-of-mass energy in Figure 1.

[a] This multiplicity refers only to charged pions.

For the $W^\pm$ t-channel (Table 1), this initial proton energy is relatively small, and the pions produced by photoproduction are therefore few ($\sim 2\pi$).

For the Z^o s-channel (Table 2), the energy is huge, so the corresponding photoproduced pion number is very large ($\sim 12\pi$).

For the W^+W^- production (Table 3), the energy is quite high, and the number of photoproduced pions is not too small ($\sim 10\pi$).[4] The probability, multiplicity, and secondary energies are easily derived, as shown in Tables 1, 2, and 3, respectively.

The successive pion decay, $\pi^\pm \rightarrow \mu^\pm + \nu$ (reactions 2a, 2b, and 2c in Tables 1, 2, and 3), and muon decay, $\mu^\pm \rightarrow e^\pm \nu_e \nu_\mu$, are the main sources of (muonic) UHE neutrinos. These *blind* neutral particles travel cosmic distances without interacting, and then reach our (neutrino) Galactic halo.

Now, the main reaction that differentiates the three possible chains in Tables 1, 2, and 3 is the UHE ν scattering onto relic ν's in the hot dark matter halo (reactions 3a, 3b, and 3c in Tables 1, 2, and 3, respectively). The incoming hitting neutrinos are of μ nature, while the target relic ones, because of their heavier mass, are preferentially τ. Indeed, the gravitational clustering of relic cosmic neutrinos in the HDM halo is more efficient for heavier (and slower) ν_{τ_r} and $\bar{\nu}_{\tau_r}$ (Zeldovich et al. 1980; Fargion 1983; Fargion et al. 1995). For instance, in analogy to the neutron stars, in an ideal *neutrino star*, the degenerated equation for the HDM galactic number density of neutrinos grows as m_ν^3. As one can easily see in Figure 1, where the different cross sections are plotted, the $W^\pm$ t-channel interaction cross section (Table 1, reaction 1) reaches an asymptotic plateau, while the Z^o s-channel cross section (Table 2, reaction 5) exhibits an interesting resonance at $s \sim M_Z^2$ (although, as discussed before, for a very narrow m_ν mass range), and decreases at higher energies. In addition, the W^+W^- production, while of some importance at $E_{\rm cm} \sim 2M_W^2$ (where it is comparable to the $W^\pm$ t-channel), also falls as $\ln(s)/s$.

The final secondaries of the Z^*, $W^\pm$, and $\tau^\pm$ decays are (according to the corresponding multiplicity and probability) a source of π^o's whose final photons may be the observed highest energy cosmic rays.

We note that the off-shell Z^*-decay channel (Table 2, reaction 5) produces a large population of π^o secondaries ($\sim$20–21 π^o).[5] The W^+W^- channel (Table 3, reaction 6) also leads to a large number of π^o ($\sim 8\ \pi^o$).[6] The most favorable chain, in terms of energetics, is the $W^\pm$ exchange in the t-channel that occurs via $\tau^\pm$ hadronic decay. The three chains, with their corresponding primordial energy and total probabilities, are summarized in Tables 1, 2, 3, and are further discussed in § 6. Furthermore, although we carried out the computations keeping the two ν_μ branches stem-

[4] The π multiplicities have been estimated by assuming the scaling law $N \propto s^{1/4}$ and the fact that the charged pions are 2/3 of the total number.

[5] The π multiplicity has been obtained from the first equation in § 6.2 of (Schmelling 1995) and by assuming that the fraction of charged particle is nearly conserved at energies higher than $s^{1/2} = M_Z$. Finally, we assumed that all the secondaries get about the same amount of energy from the off-shell Z^* decay.

[6] The π multiplicity has been obtained by supposing that the $W^\pm$ hadronic decays are similar to the Z^o ones. The Z^o hadron multiplicities can be found in Knowles et al. (1996).

TABLE 5

MAIN W^+W^- CHANNEL REACTION CHAINS FOR FINAL PROTON PRODUCTION

Reaction	Probability	Multiplicity	Secondary Energy (eV)
1e:			
$p + \gamma \to (p, n) + 8\pi$	$P_{1e} \simeq 1$	$M_{1e} = 5$[a]	$E_\pi \sim E_p/9$
2e:			
$\pi^+ \to \mu^+ + \nu_\mu$			
$\pi^- \to \mu^- + \bar{\nu}_\mu$	$P_{2e} \simeq 1$	$M_{2e} = 1$	$E_\nu \sim 0.21 E_\pi = 2.3 \times 10^{-2}\ E_p$
2e′:			
$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$			
$\mu^- \to e^- + \bar{\nu}_e + \nu_\mu$	$P_{2e'} \simeq 1$	$M_{2e'} = 1$	$E_\nu \sim 0.26 E_\pi = 2.8 \times 10^{-2}\ E_p$
3e:			
$\nu_\mu + \bar{\nu}_{\mu_r} \to W^+ + W^-$			
$\bar{\nu}_\mu + \nu_{\mu_r} \to W^+ + W^-$	$P_{\nu\nu} = \sigma_{\nu_\mu \bar{\nu}_\mu} n_{\nu_r} l_g \sim 1.2 \times 10^{-4}$–$10^{-2}$	$M_{3e} = 2$	$E_W \sim E_{\nu_\mu}/2 = 1.1 \times 10^{-2}\ E_p$
3e′:			
$\nu_\mu + \bar{\nu}_{\mu_r} \to W^+ + W^-$			
$\bar{\nu}_\mu + \nu_{\mu_r} \to W^+ + W^-$	$P_{\nu\nu} = \sigma_{\nu_\mu \bar{\nu}_\mu} n_{\nu_r} l_g \sim 10^{-4}$–$10^{-2}$	$M_{3e'} = 2$	$E_W \sim E_{\nu_\mu}/2 = 1.4 \times 10^{-2}\ E_p$
4e:			
$W^\pm \to p + X$	$P_{4e} \sim 0.7$	$M_{4e} = 0.8$	$E_p \sim E_W/33 = 3.5 \times 10^{-4}\ E_p$
4e′:			
$W^\pm \to p + X$	$P_{4e'} \sim 0.7$	$M_{4e'} = 0.8$	$E_p \sim E_W/33 = 4.3 \times 10^{-4}\ E_p$
Totals:	${}^{e}P_{\rm tot}^{WW} = \Pi_i M_i P_i \sim 6.6 \times 10^{-4}$–$10^{-2}$		
	${}^{e'}P_{\rm tot}^{WW} = \Pi_i M_i P_i \sim 5.6 \times 10^{-4}$–$10^{-2}$		$E_p^{WW} \sim 7.3 \times 10^{23}$
Additional reactions not included in the present analysis			
W^+W^- channels if there is neutrino flavor mixing $\nu_\mu \leftrightarrow \nu_\tau$:			
3′e:			
$\bar{\nu}_\tau + \nu_{\tau_r} \to W^+ + W^-$			
$\nu_\tau + \bar{\nu}_{\tau_r} \to W^+ + W^-$			
W^+W^- channel whose efficiency is suppressed by lower ν_e, $\bar{\nu}_e$ energies and n_{ν_e}, $n_{\bar{\nu}_e}$ densities:			
3″e:			
$\bar{\nu}_e + \nu_{e_r} \to W^+ + W^-$			

NOTE.—In calculating the probability for the ν-ν interaction we assumed: $n_{\nu_r} = 10^{7-9}\ {\rm cm}^{-3}$, $l_g \sim 10^{24}$ cm. The $\sigma_{\nu_\mu \bar{\nu}_\tau}$ value has been obtained from the corresponding cross section and center-of-mass energy in Figure 1.

[a] This multiplicity refers only to charged pions.

ming from the π and μ decays split for the sake of completeness, now we will refer to the specified chain probability as the sum of these two previous calculations.

Another way to get electronic antineutrinos is from the neutron beta decay in flight. These $\bar{\nu}_e$'s are extremely energetic and very good candidates for energy transfer. Unfortunately, the free neutron decay, usually important at ultrahigh energies of the order of $E_n \sim 10^{20}$ eV, becomes less and less competitive at higher Lorentz boosts. Indeed, at the energies higher than 10^{21} eV we are interested in here, the neutron mean free path is nearly an order of magnitude larger than the corresponding interaction length for neutrons interacting with the 2.73 K BBR in the photoproduction of pions. We recall these $\bar{\nu}_e$'s from neutron decay, even if quite rare, since they require a primordial proton energy lower than the proposed channels. Indeed, the main artery for the UHE neutrino production is photopion multiproduction by protons: $p\gamma_{\rm BBR} \to p + N\pi$, $p\gamma_{\rm BBR} \to n + N\pi$, with $N \geq 2$. The neutron, being itself a proton secondary, will begin its chain with a degraded energy, and so with a less favorable rate for the $\pi^\pm$ production.

Let us remark here that in the UHE neutrino-neutrino scattering, the electron neutrino coming from μ decay can play an important role. Hence, one could consider the W exchange interactions ν_e-$\bar{\nu}_r$ (or $\bar{\nu}_e$-ν_r), and in particular ν_e-$\bar{\nu}_{\tau_r}$ and $\bar{\nu}_e$-ν_{τ_r}, as a source of UHE electron secondaries. In principle, such UHE electrons could convert half of their energy into photons by inverse Compton scattering (ICS) on BBR (Fargion & Salis 1998). This reaction, being so short, is very efficient in UHE photon production. The ICS in the Galactic halo, while being dominant up to $E_e \sim m_e^2/(h\nu_{\rm opt}) \sim 2 \times 10^{11}$ eV over the competitive synchrotron radiation, no longer rules at very high energies. Indeed, since for $E_e > m_e^2/(h\nu_{\rm opt})$ the Klein-Nishina cross section decreases linearly with the electron energy, the synchrotron radiation losses (and the corresponding interaction lengths) are larger (or smaller) than the ICS radiation losses by 6 orders of magnitude (since synchrotron interaction works at the Thomson constant regime) for UHE electrons with energies of $E_e \gg m_e^2/(h\nu_{\rm BBR}) \sim 4 \times 10^{14}$ eV, and in particular for $E_e \sim 10^{21}$ eV. Therefore, we must expect only an associated parasite electromagnetic shower at the characteristic synchrotron radiation energy, $E_\gamma \simeq 1.6 \times 10^{16}\ {\rm eV}\ (E_e/10^{21}\ {\rm eV})^2$, with a lower but significant flux of energy with respect to the UHE CR, possibly in the same direction, but at a delayed time. Moreover, because of these synchrotron radiation losses, the interaction length for synchrotron radiation for the electrons inside our Galaxy ($B_G \sim 3 \times 10^{-6}$ G) is reduced to $\lambda_e \simeq 120$ pc. Therefore, the probability that such an electron is the progenitor of the observed signal at the Fly's Eye detector is negligible. Specifically, this probability is $P_e \simeq \sigma_{\nu\nu_r} n_{\nu_r} \lambda_e \eta_n \sim 3 \times 10^{-8}$, where $\eta_n \sim (10^{20}\ {\rm eV}/E_n)$ is the efficiency for β decay. A more interesting probability is obtained if we consider the electrons coming via the t-channel from τ decay. In this case we get $P_\tau \sim 10^{-5}$, where now $\lambda_e \simeq l_g$, and $E_p \sim 2.2 \times 10^{22}$ eV for the initial proton energy.

5. THE CHAIN REACTIONS LEADING TO THE FINAL PROTONS

We now consider the reactions giving rise to final protons. This analysis has a particular importance because local effects could disfavor a shower initiated by a 320 EeV photon. In fact, the interaction between the UHE photon and the virtual photons of the stationary geomagnetic field leads to an electromagnetic cascade whose maximum is not in agreement with the observed data of the Fly's Eye event (Burdman, Halzen, & Gandhi 1997).

Let us examine the steps leading to the final protons, summarized in Tables 4 and 5. The first three processes in the two chains are the same as for the final photon production. The photoproduction of pions creates charged pions whose decay generates UHE neutrinos that are able to reach the Galactic halo, filled up with relic ν's. Now, the ν-ν interactions either occur via a Z^* exchange (Table 4), or can create a W^+W^- pair (Table 5). Both the Z^* and the W can then undergo a subsequent hadronic decay (Table 5). In the first case, at the relevant Z^* center-of-mass energy one gets an average of two protons in each hadronic final state, while from the on-shell W hadronic decay one expects, on average, just one proton. As in the previous section, we derive the corresponding probability and initial proton energy. The main difference from the similar photon channels (Tables 1, 2, and 3) is the lack of a t-channel, owing to the absence of τ decays into protons. We also note the more promising role of the W^+W^- channel over the Z^o channel.

Let us now compare the results for the photon and proton chains. The Z-channel for photons has a better probability but requires a higher initial energy than the analogous one for protons. These differences are related to the fact that protons are less abundant than pions, which moreover must still decay into photons. Therefore, the pions need a higher center-of-mass energy, but the consequent depletion of the cross section is balanced by the larger multiplicity. A similar behavior can be found in the W^+W^- channel for photons and protons. The difference in the initial energy is just the factor of 2 that stems from the pion decay into photons, while the difference in the probability is again related to the different multiplicity.

As we discuss further below, the W^+W^- channel into protons could indeed provide a solution to the 320 EeV event. The necessary initial proton energy ($\sim 7.3 \times 10^{23}$) is quite high, but the probability ($\geq 1.2 \times 10^{-3}$) is at least 120 times more favorable than is required for the direct travel of a proton from the source to the Earth. Moreover, and most importantly, such a complicated sequence of reactions explains the embarrassing absence of the expected hundreds of cosmic-ray signals at EeV energies that would have to be present for a direct proton propagation.

6. CONCLUSIONS

As summarized in Tables 1, 2, and 3 for the final photons, and in Tables 4 and 5 for the final protons, antiprotons, neutrons, and antineutrons, the probabilities and primordial energies for proton and neutron chains for the W, Z, and WW channels are able to give extragalactic solutions to the UHE puzzle. The neutrinos could be the *ambassadors* of cosmic energetic sources, whose energies are finally converted by the relic massive neutrino halo calorimeter into UHE photons or protons. The approximate lower bound on the total probability and the required initial proton energy for the different channels and for a relic neutrino mass $m_\nu \sim 10$ eV are:

Table 1 (γ): $P_{\rm tot}^W \geq 10^{-3}$, $E_p^W \simeq 4.4 \times 10^{22}$ eV .
Table 2 (γ): $P_{\rm tot}^Z \geq 6.2 \times 10^{-3}[m_\nu/(10\ {\rm eV})]^{-1}$, $E_p^Z \simeq 3 \times 10^{24}$ eV .
Table 3 (γ): $P_{\rm tot}^{WW} \geq 2 \times 10^{-2}[m_\nu/(10\ {\rm eV})]^{-1}$, $E_p^{WW} \simeq 1.8 \times 10^{24}$ eV .
Table 4 (p): $P_{\rm tot}^Z \geq 5.1 \times 10^{-4}[m_\nu/(10\ {\rm eV})]^{-1}$, $E_p^Z \simeq 10^{24}$ eV .
Table 5 (p): $P_{\rm tot}^{WW} \geq 1.2 \times 10^{-3}[m_\nu/(10\ {\rm eV})]^{-1}$, $E_p^{WW} \simeq 7.3 \times 10^{23}$ eV .

In the four last probabilities we indicate just the main neutrino mass dependence; the exact one is a more complicated function. This analysis shows that the $W^\pm$ channel for photons and the W^+W^- channel for protons give the most reasonable combination of the total probability and initial proton energy. These probability values are at least 3 orders of magnitude above the corresponding ones for a *direct* neutrino interaction on the terrestrial atmosphere. The required primordial sources can be safely located at any cosmic distance escaping the GZK cutoff. The Seyfert galaxy MCG 8-11-11, which is very close to the arrival direction of the 320 EeV shower and located at a redshift of $z = 0.0205$ ($D \simeq 70$ Mpc H_{100}^{-1}), would be a very natural candidate. Its large observed luminosity in low-energy gamma radiation ($L_\gamma \sim 7 \times 10^{46}$ ergs s^{-1}) is of the order of magnitude needed to explain the UHE energetics within our present scheme. Indeed, the total energy needed for any (spherical) source at a distance D to give rise to the 320 EeV event in our approach is $E_s = (E_p 4\pi D^2)/(AP)$, where A is the Fly's Eye detector area [$\sim$(30 Km)^2] and P is the probability of any given channel. The corresponding power a source would need to get a rate of just one event per yr for the W, Z, and WW channels, respectively, and for the most conservative value of the ν-ν interaction probability, is

Table 1 (γ): $\dot{E}_s^W \sim 2.2 \times 10^{47}(D/100\ {\rm Mpc})^2$ ergs s^{-1} .
Table 2 (γ): $\dot{E}_s^Z \sim 2 \times 10^{48}(D/100\ {\rm Mpc})^2$ ergs s^{-1} .
Table 3 (γ): $\dot{E}_s^{WW} \sim 3.7 \times 10^{47}(D/100\ {\rm Mpc})^2$ ergs s^{-1} .
Table 4 (p): $\dot{E}_s^Z \sim 8.1 \times 10^{48}(D/100\ {\rm Mpc})^2$ ergs s^{-1} .
Table 5 (p): $\dot{E}_s^{WW} \sim 2.5 \times 10^{48}(D/100\ {\rm Mpc})^2$ ergs s^{-1} .

These values may be overestimated by 1 or 2 orders of magnitude if the relic neutrino clustering is more efficient. In any case, they are clearly comparable to the MeV observed power from MCG 8-11-11. The energetic and directional *resonance* toward this source, and the quite natural hypothesis that at least a (τ) neutrino mass falls in the range of a few tens of eV, as expected in the HCDM standard cosmological model, seem to favor our solution of the UHE CR puzzle. Nevertheless, we believe that more theoretical and experimental investigations are needed to provide more convincing evidence of an extended dark neutrino halo, and possibly even to give an indirect estimate of the neutrino mass.

We thank Dario Grasso for bringing Roulet (1993) to our attention. We also thank A. Aiello, R. Conversano, and M. Grossi for their careful reading of the manuscript.

REFERENCES

Berezinsky, V. S., & Gazirov, A. Z. 1977, J. Exp. Theor. Phys. Lett., 254, 25
Bird, D. J., et al. 1994, ApJ, 424, 491
Burdman, G., Halzen, F., & Gandhi, R. 1997, preprint hep-ph/9709399
Clark, T. A., Brown, L. W., & Alexander, J. K. 1970, Nature, 228, 847
Dar, A., & Laor, A. 1997, ApJ, 478, L5
Elbert, J. W., & Sommers, P. 1995, ApJ, 441, 151
Enqvist, K., Kainulainen, K., & Maalampi, J. 1989, Nucl. Phys. B, 317, 647
Fargion, D. 1983, Nuovo Cimento, B77, 111
———. 1997, ApJ, submitted (preprint astro-ph/9704205)
Fargion, D., Konoplich, R. V., & Salis, A. 1997, Z. Phys. C, 74, 571
Fargion, D., & Salis, A. 1995, Nucl. Phys. B (Proc. Suppl.), 43, 269
———. 1998, Phys. Uspekhi, 41(8), 823
———. 1997, in Proc. 25th Int. Cosmic-Ray Conference (Potchetstroomse, South Africa), 157
Fargion, D., et al. 1995, Phys. Rev. D, 52, 1828
Fargion, D., et al. 1996, Phys. Lett. B, 375, 223
Gandhi, R., et al. 1996, Astropart. Phys., 5, 81
Glashow, S. L. 1960, Phys. Rev., 118, 316
Gould, R. J., & Schreder, G. 1966, Phys. Rev. Lett., 16, 252
Greisen, K. 1966, Phys. Rev. Lett., 16, 748
Knowles, I. G., et al. 1996, in Physics at LEP2 (CERN Rept. 96-01), 103
Longair, M. S. 1994, High Energy Astrophysics, Vol. 2 (Cambridge: Cambridge Univ. Press)
Medina-Tanco, G. A. 1997, preprint astro-ph/9610172
Particle Data Group. 1996, Phys. Rev. D, 54, 1
Protheroe, R. J., & Biermann, P. L. 1996, Astropart. Phys., 6, 45
Roulet, E. 1993, Phys. Rev. D, 47, 5247
Schmelling, M. 1995, Phys. Scr., 51, 683
Zat'sepin, G. T., & Kuz'min, V. A. 1966, J. Exp. Theor. Phys. Lett., 4, 78
Zeldovich, Ya. B., et al. 1980, Soviet J. Nucl. Phys., 31, 664