Possible detection of relic neutrinos and their mass

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Abstract. Recently the possibility was widely discussed that a large fraction of the highest energy cosmic rays may be decay products of Z bosons which were produced in the resonant annihilation of ultrahigh energy cosmic neutrinos on cosmological relic neutrinos. If one takes this so-called Z-burst scenario seriously, one may infer the mass of the heaviest relic neutrino as well as the necessary ultrahigh energy cosmic neutrino flux from a comparison of the predicted Z-burst spectrum with the observed cosmic ray spectrum.

1 Introduction

Big bang cosmology predicts the existence of a background gas of free photons and neutrinos. The measured cosmic microwave background radiation (CMBR) supports the applicability of standard cosmology back to photon decoupling which occured approximately one hundred thousand years after the big bang. The relic neutrinos, on the other hand, have decoupled when the universe had a temperature of 1 MeV and an age of just one second. Thus, a measurement of the relic neutrinos, with a predicted average number density of

$$\langle n_{\nu_i} \rangle = \frac{3}{22} \langle n_\gamma \rangle \simeq 56 \text{ cm}^{-3},$$

(1)

per light neutrino species $i$ ($m_{\nu_i} < 1$ MeV), would provide a new window to the early universe. Their predicted number density is comparable to the one of the microwave photons. However, since neutrinos interact only weakly, the relic neutrinos have not been detected until now.

Recently, an indirect detection possibility for relic neutrinos has been discussed (Fargion et al., 1999; Weiler, 1999). It is based on so-called Z-bursts resulting from the resonant annihilation of ultrahigh energy cosmic neutrinos (UHEC\nu s) with relic neutrinos into Z bosons (Weiler, 1982; Roulet, 1993; Yoshida et al., 1997), the force carriers of the electro-weak neutral current (cf. Fig. 1). On resonance, the corresponding cross section is enhanced by several orders of magnitudes. If neutrinos have non-vanishing masses $m_{\nu_i}$ – for which there is rather convincing evidence in view of the observations of neutrino oscillations (Groom et al., 2000) – the resonance energies, in the rest system of the relic neutrinos, correspond to

$$E_{\nu_i}^{\text{res}} = \frac{M_Z^2}{2 m_{\nu_i}} = 4.2 \cdot 10^{21} \text{ eV} \left(\frac{1 \text{ eV}}{m_{\nu_i}}\right),$$

(2)

with $M_Z$ denoting the mass of the Z boson. These resonance energies are, for neutrino masses of $O(1)$ eV, remarkably close to the energies of the highest energy cosmic rays. Indeed, it was argued (Fargion et al., 1999; Weiler, 1999) that the ultrahigh energy cosmic rays (UHECRs) above the predicted Greisen-Zatsepin-Kuzmin (GZK) cutoff (Greisen, 1966; Zatsepin and Kuzmin, 1966; Bhattacharjee and Sigl, 2000) around $4 \cdot 10^{19}$ eV are mainly protons (and, maybe, photons) from Z decay.

Fig. 1. Illustration of a Z-burst resulting from the resonant annihilation of an ultrahigh energy cosmic neutrino on a relic (anti-)neutrino (adapted from Ref. (Päs and Weiler, 2001)).
This hypothesis was discussed in several papers (Waxman, 1998; Yoshida et al., 1998; Gelmini and Kusenko, 1999, 2000; Blanco-Pillado et al., 2000; Pääs and Weiler, 2001; Fargion et al., 2001; McKellar et al., 2001). Here, we review the Z-burst scenario and report on a recent quantitative investigation (Fodor et al., 2001a, in prep.), where an attempt was made to determine the mass of the heaviest relic neutrino as well as the necessary UHECR flux by comparing the predicted cosmic ray spectrum from Z-bursts with the observed one via a maximum likelihood analysis.

2 Z-burst spectrum

A comparison of the Z-burst scenario with the observed ultrahigh energy cosmic ray spectrum proceeds essentially in four steps. First, one has to determine the probability of Z production as a function of the distance from Earth. Secondly, one exploits data from collider experiments to derive the energy distribution of the produced protons in the lab system. Thirdly, one has to take into account the propagation of the protons to Earth, i.e. one has to determine their energy losses due to pion and $e^+e^-$ production through scattering on the CMBR and due to their redshift. The last step is the comparison of the predicted and observed spectra and the extraction of the mass of the relic neutrino and the necessary UHECR flux.

The contribution of protons from Z-bursts to the UHECR flux can be summarized as (Fodor et al., 2001a, in prep.)

$$F_{p|Z}(E) = \sum_{i}^{\infty} \int_{0}^{\infty} dE_{p} \int_{0}^{\infty} dr \int_{0}^{\infty} de \times \left[ F_{\nu_i}(E_{\nu_i}, r) n_{\nu_i}(r) + F_{\bar{\nu}_i}(E_{\bar{\nu}_i}, r) n_{\nu_i}(r) \right] \times \sigma_{\nu_i\bar{\nu}_i}(\epsilon) Br(Z \to \text{hadrons}) Q_{p+n}(E_p) \times \left( -\frac{\partial}{\partial E} P(r, E_p; E) \right),$$

where $E$ is the energy of the protons arriving at Earth. Further important ingredients in Eq. (3) are: the ultrahigh energy cosmic neutrino fluxes $F_{\nu_i}(E_{\nu_i}, r)$ at the resonant energies $E_{\nu_i} \approx E_{\nu_i}^{\text{res}}$ and at distance $r$ to Earth, the number density $n_{\nu_i}(r)$ of the relic neutrinos, the Z production cross section $\sigma_{\nu_i\bar{\nu}_i}(\epsilon)$ at centre-of-mass (cm) energy $\epsilon = \sqrt{2m_{\nu_i}E_{\nu_i}}$, the branching ratio for $Z$ to hadrons, $Br(Z \to \text{hadrons})$, the energy distribution $Q_{p+n}(E_p)$ of the produced protons (and neutrons) with energy $E_p$ and the probability $P(r, E_p; E)$ that a proton created at a distance $r$ with energy $E_p$ arrives at Earth above the threshold energy $E$.

The last four building blocks, $\sigma_{\nu_i\bar{\nu}_i}$, the hadronic branching ratio, $Q$, and $P$, are very well determined, whereas the first two ingredients, the flux of UHECRs, $F_{\nu_i}(E_{\nu_i}, r)$, and the relic neutrino number density $n_{\nu_i}(r)$, are much less accurately known. In the following we shall discuss all these ingredients in detail.

2.1 Z production and decay

At LEP and SLC millions of Z bosons were produced and their decays analyzed with extreme high accuracy. Due to the large statistics, the uncertainties of the analysis related to Z decay are negligible.

Fodor et al. (2001a, in prep.) combined existing published (Akers et al., 1994; Abe et al., 1999; unpublished) data on the momentum distribution $P_{p}(x) = dN_{p}/dx$, with momentum fraction $x = p_{\text{proton}}/p_{\text{beam}}$, of protons ($p$) (plus antiprotons ($\bar{p}$)) in Z decays, see Fig. 2 (top). The $p + \bar{p}$ multiplicity is $\langle N_{p} \rangle = \int_{0}^{1} dx P_{p}(x) = 1.04 \pm 0.04$ in the hadronic channel (Groom et al., 2000).

The energy distribution $Q_{p}(E_p)$ of the produced protons with energy $E_p$ entering in the spectrum (3) is obtained after a Lorentz transformation from the cm system to the lab system, in which the target relic neutrino is at rest. It is only a function of $y = 2E_{p}/E_{\nu}$ and displayed in Fig. 2 (bottom).

Neutrons produced in Z decays will decay and end up as...
UHECR protons. They are taken into account according to
\[ Q_{p+n}(y) = \left( 1 + \frac{\langle N_n \rangle}{\langle N_p \rangle} \right) Q_p(y), \]
where the neutron ($n$) (+ antineutron ($\bar{n}$)) multiplicity, $\langle N_n \rangle$, is $\approx 4\%$ smaller than the proton’s (Biebel, priv. comm.).

2.2 Propagation of nucleons through the CMBR

Similarly, the CMBR is known to a high accuracy. It plays an important role in the determination (Bahcall and Waxman, 2000; Fodor and Katz, 2001a) of the probability $P(r, E_p, E)$, which takes into account the fact that protons of extragalactic (EG) origin and energies above $\approx 4 \times 10^{19}$ eV lose a large fraction of their energies (Greisen, 1966; Zatsepin and Kuzmin, 1966) due to pion and $e^+e^-$ production through scattering on the CMBR and due to their redshift. $P(r, E_p, E)$, in the form as it has been calculated for a wide range of parameters by Fodor and Katz (2001a), is an indispensable tool in the quantitative analysis in Refs. (Fodor et al., 2001a, in prep.). In addition to its already published (Fodor and Katz, 2001a) parametrized form, the numerical data for the probability distribution $-\partial P(r, E_p, E)/\partial E$ are now available via the World-Wide-Web URL www.desy.de/~uhecr.

2.3 UHECR fluxes

Presently unknown ingredients in the evaluation of the Z-burst spectrum (3) are the differential fluxes $F_{\nu}$ of ultrahigh energy cosmic neutrinos (see e.g. Refs. (Protheroe, 1999; Gandhi, 2000; Learned and Mannheim, 2000) for recent reviews). Present experimental upper limits on these fluxes are rather poor (cf. Fig. 3 and contributions to these proceedings (Seckel et al., 2001; Yoshida et al., 2001)).

What are the theoretical expectations? More or less guaranteed are the so-called cosmogenic neutrinos which are produced when ultrahigh energy cosmic protons scatter inelastically off the cosmic microwave background radiation (Greisen, 1966; Zatsepin and Kuzmin, 1966) in processes such as $p\gamma \rightarrow \Delta \rightarrow n\pi^+$, where the produced pions subsequently decay (Berezinsky and Zatsepin, 1969, 1970). These fluxes (for recent estimates, see (Yoshida and Teshima, 1993; Protheroe and Johnson, 1996; Yoshida et al., 1997; Engel and Staney, 2001)) represent reasonable lower limits on the ultrahigh energy cosmic neutrino flux, but turn out to be insufficient for the Z-burst scenario. Recently, theoretical upper limits on the ultrahigh energy cosmic neutrino flux have been given by Waxman and Bahcall (1999), Mannheim et al. (2001), and Bahcall and Waxman (2001). Per construction, the upper limit from “visible” hadronic astrophysical sources, i.e. from those sources which are transparent to ultrahigh energy cosmic protons and neutrons, is of the order of the cosmogenic neutrino flux (Waxman and Bahcall, 1999; Mannheim et al., 2001; Bahcall and Waxman, 2001) and shown in Fig. 3 (“WB”). Also shown in this figure (“MPR”) is the much larger upper limit from “hidden” hadronic astrophysical sources, i.e. from those sources from which only photons and neutrinos can escape (Berezinsky, 1979; Mannheim et al., 2001).

In this situation of insufficient knowledge, the following approach concerning the flux of ultrahigh energy cosmic neutrinos was taken in Refs. (Fodor et al., 2001a, in prep.). The flux was assumed to have the form
\[ F_{\nu}(E_{\nu}, r) = F_{\nu}(E_{\nu0}, 0)(1 + z)^\alpha, \]
where $z$ is the redshift and where $\alpha$ characterizes the source evolution (see also (Yoshida et al., 1997; Yoshida et al., 1998)). The flux at Earth, $F_{\nu}(E_{\nu0}, 0)$, or, more accurately, the sum of the corresponding fluxes at the resonant energies,
\[ F_Z = \sum_i \left[ F_{\nu}(E_{\nu}^{\text{res}}) + F_{\bar{\nu}}(E_{\bar{\nu}}^{\text{res}}) \right], \]
was then determined, together with the neutrino mass, by a fit to the UHECR data. This analysis went up to distances $R_0$ (cf. (3)) corresponding to redshift $z = 2$ (cf. (Waxman, 1995)), and uncertainties in the Hubble expansion rate $H_0 = 100 \text{ km s}^{-1} \text{ Mpc}^{-1}$, as given in Ref. (Groom et al., 2000), were included.

2.4 Relic neutrino number density

The dependence of the relic neutrino number density $n_{\nu}$, on the distance $r$ was treated in the following way in Refs. (Fodor et al., 2001a, in prep.). The question is whether there is remarkable clustering of the relic neutrinos within the local GZK zone of about 50 Mpc. It is known that the density distribution of relic neutrinos as hot dark matter follows the total mass distribution; however, with less clustering (Ma, 1999; Primack and Gross, 2000). In fact, for $m_{\nu_1} \lesssim 1$ eV, one expects pretty much that the neutrino number density equals the big bang prediction (1) (Primack, priv. comm.).
3 Determination of \( m_\nu \) and the UHECR flux

The predicted spectrum of protons from Z-bursts (3) can now be compared with the observed ultrahigh energy cosmic ray spectrum (cf. Fig. 5). The analysis in Refs. (Fodor et al., 2001a, in prep.) included published and unpublished (from the World-Wide-Web pages of the experiments on 17/03/01) UHECR data of AGASA (Takeda et al., 1998, 1999), Fly’s Eye (Bird et al., 1993, 1994, 1995), Haverah Park (Lawrence et al., 1991; Ave et al., 2000), and HIRES (Kieda et al., 2000). Due to normalization difficulties the Yakutsk (Efimov et al., 1991) results were not used.

As usual, each logarithmic unit between \( \log(E/\text{eV}) = 18 \) and \( \log(E/\text{eV}) = 26 \) was divided into ten bins. The predicted number of ultrahigh energy cosmic ray events in a bin was taken as

\[
N(i) = \int_{E_i}^{E_{i+1}} \frac{\text{d}E}{E} \left[ F_{p|\text{bkd}}(E; A, \beta) + F_{p|Z}(E; F_Z, m_\nu) \right],
\]

where \( E_i \) is the lower bound of the \( i \text{-th} \) energy bin. The first, background term \( F_{p|\text{bkd}}(E; A, \beta) \) was taken to have the usual power-law behavior which describes the data well for smaller energies (Takeda et al., 1998, 1999). The second term of the flux in Eq. (7) corresponds to the spectrum of the Z-bursts, Eq. (3).

Two possibilities for the background term were studied. In the first case it was assumed that the power part is produced in our galaxy. Thus no GZK effect was included for it (“halo”), and it was taken as,

\[
F_{p|\text{bkd}}(E; A, \beta) = A \cdot E^{-\beta} \quad (\text{halo}).
\]

In the second – in some sense more realistic – case it was assumed that the background protons come from uniformly distributed, extragalactic sources and suffer from the GZK cutoff (“EG”). In this case, \( A \cdot E_p^{-\beta} \) was taken as an injection spectrum, and the simple power-law like term was modified, by taking into account the probability \( P(r, E_p; E) \),

\[
F_{p|\text{bkd}}(E; A, \beta) = \int_0^{R_0} \text{d}E_p \int_0^{R_0} \text{d}r \cdot A \cdot E_p^{-\beta} \left( -\frac{\partial P(r, E_p; E)}{\partial E} \right) (\text{EG}).
\]

It falls off around \( 4 \cdot 10^{19} \text{ eV} \) (see Fig. 5 (bottom)).

Note that the following implicit assumptions have been made through ansatz (7): \( i \) It was assumed that the ultrahigh energy photons from Z-bursts can be neglected. \( ii \) It was assumed that there are no significant additional primary ultrahigh energy proton fluxes beyond the extrapolation of the above power-law. Assumption \( i \) can be justified on account of the result of a detailed study (Fodor et al., in prep.) of the boosted Z-decay (data from Refs. (Akers et al., 1994; Abreu et al., 1995; Buskulic et al., 1995; Abe et al., 1999, unpublished)) which show that the energy of the photons is peaked at \( 1.7 \cdot 10^{18} \text{ eV}/m_\nu \text{ eV} \), at which the attenuation...
Fig. 5. The available UHECR data with their error bars and the best fits from Z-bursts, for nearly degenerate neutrino masses, \( m_{\nu} \approx m_{\nu} \), and for cosmological evolution parameter \( \alpha = 3 \) (Fodor et al., 2001a, in prep.). Top: Best fit for the “halo”-case (solid line). The bump around \( 4 \cdot 10^{19} \) eV is due to the Z-burst protons (dashed-dotted), whereas the almost horizontal contribution (dashed) is the first, power-law-like term of Eq. (7). Bottom: “Extragalactic”-case. The first bump at \( 4 \cdot 10^{19} \) eV represents protons produced at high energies and accumulated just above the GZK cutoff due to their energy losses. The bump at \( 3 \cdot 10^{21} \) eV is a remnant of the Z-burst energy. The dashed line shows the contribution of the power-law-like spectrum with the GZK effect included. The predicted fall-off for this term around \( 4 \cdot 10^{19} \) eV can be observed.

The contribution of ultrahigh energy photons from Z decay in the observed UHECR spectrum is far less relevant than that of the protons. Assumption ii) will be relaxed in Ref. (Fodor et al., in prep.).

The expectation value for the number of events in a bin is given by Eq. (7). To determine the most probable value for \( m_{\nu} \), the maximum likelihood method was used and the \( \chi^{2}(\beta, A, F_{Z}, m_{\nu}) \) (Fodor and Katz, 2001b),

\[
\chi^{2} = \sum_{i=185}^{26.0} 2 \left[ N(i) - N_{o}(i) + N_{o}(i) \ln \left( N_{o}(i)/N(i) \right) \right],
\]

was minimized, where \( N_{o}(i) \) is the total number of observed events in the \( i \)-th bin. Since the Z-burst scenario results in a quite small flux for lower energies, the “ankle” was used as a lower end for the UHECR spectrum: \( \log(E_{\text{min}}/\text{eV}) = 18.5 \). The results are insensitive to the definition of the upper end (the flux is extremely small there) for which \( \log(E_{\text{max}}/\text{eV}) = 26 \) was chosen. The uncertainties of the measured energies are about 30% which is one bin. Using a Monte-Carlo method this uncertainty was included in the final error estimates.

In the case where there are three neutrino types with nearly degenerate neutrino masses, \( m_{\nu} \approx m_{\nu} \), the fitting procedure involves four parameters: \( \beta, A, F_{Z} \) and \( m_{\nu} \). The minimum of the \( \chi^2(\beta, A, F_{Z}, m_{\nu}) \) function is \( \chi^2_{\text{min}} \) at \( m_{\nu} \text{min} \) which is the most probable value for the mass, whereas the 1 \( \sigma \) (68%) confidence interval for \( m_{\nu} \) is determined by

\[
\chi^2(\beta', A', F_{Z}', m_{\nu}) \equiv \chi^2_{\nu}(m_{\nu}) = \chi^2_{\text{min}} + 1. \quad (11)
\]

Here \( \beta', A', F_{Z}' \) are defined in such a way that the \( \chi^{2} \) function is minimized in \( \beta, A \) and \( F_{Z} \), at fixed \( m_{\nu} \).

Qualitatively, the analysis can be understood in the following way. In the Z-burst scenario a small relic neutrino mass needs large \( E_{\nu}^{\text{res}} \) in order to produce a Z. Large \( E_{\nu}^{\text{res}} \) results in a large Lorentz boost, thus large \( E_{p} \). In this way the shape of the detected energy (E) spectrum determines the mass of the relic neutrino. The sum of the necessary UHEC fluxes \( F_{Z} \), on the other hand, is determined by the over-all normalization.

The best fits to the observed data can be seen in Fig. 5, for evolution parameter \( \alpha = 3 \). For the “halo”-case, a neutrino mass of \( 2.75^{+1.28}_{-0.97}(3.15) \) eV was found, whereas, for the “EG”-case, the fit yielded \( 0.26^{+0.50}_{-0.34}(0.22) \) eV. The first numbers are the \( 1 \sigma \), the numbers in the brackets are the \( 2 \sigma \) errors. This gives an absolute lower bound on the mass of the heaviest \( \nu \) of 0.06 eV at the 95% confidence level (CL). Note, that the surprisingly small uncertainties are based on the above \( \chi^{2} \) analysis and dominantly statistical ones. The fits are rather good; for 21 non-vanishing bins and 4 fitted parameters they can be as low as \( \chi^2 = 18.6 \). The neutrino mass was determined for a wide range of cosmological source evolution \( (\alpha = 0 \pm 3) \) and Hubble parameter \( (H_{0} = (71 \pm 7) \times 10^{-5} \text{km/sec/Mpc}) \) and was found to depend only moderately on them. The results remained within the above error bars. A Monte-Carlo analysis was performed studying higher statistics. In the near future, Auger (Guerrard, 1999; Bertou et al., 2000) will provide a ten times higher statistics, which reduces the error bars in the neutrino mass to \( \approx \) one third of their present values.

The necessary UHEC\( \nu \) fluxes at \( E_{\nu}^{\text{res}} \) have been obtained from the fits. They are summarized in Fig. 6, together with some existing upper limits and projected sensitivities of present and future projects. The necessary UHEC\( \nu \) flux appears to be well below present upper limits and is within the expected sensitivity of AMANDA, Auger, and OWL. An important constraint for all top-down scenarios (Bhattacharjee and Sigl, 2000) is the EGRET observation of a diffuse \( \gamma \) background (Sreekumar et al., 1998). As a cross check, one may calculate the total energy in photons from Z-bursts. Even if one assumes that all their energy ends up between 30 MeV and 100 GeV, one finds that the \( \gamma \)
flux is somewhat smaller than that of EGRET. These numerical findings are in fairly good agreement with simulations done by Sigl (priv. comm.) (cf. Fig. 7 (top)).

4 Comparison with $\Delta m^2_{\nu}$ from neutrino oscillations

One of the most attractive patterns for neutrino masses is similar to the one of the charged leptons or quarks: the masses are hierarchical, thus the mass difference between the families is approximately the mass of the heavier particle. Using the mass difference of the atmospheric neutrino oscillation for the heaviest mass (Groom et al., 2000), one obtains values between 0.03 and 0.09 eV. It is an intriguing feature of the result found in Refs. (Fodor et al., 2001a, in prep.) that the smaller one of the predicted masses is compatible on the $\approx 1.3 \sigma$ level with this scenario.

Another popular possibility is to have 4 neutrino types. Two of them – electron and sterile neutrinos – are separated by the solar neutrino oscillation solution, the other two – muon and tau – by the atmospheric neutrino oscillation solution, whereas the mass difference between the two groups is of the order of 1 eV. This possibility was studied, too. On the mass scales and resolution considered, the electron and sterile neutrinos are practically degenerate with mass $m_1$ and the muon and tau neutrinos are also degenerate with mass $m_2$.

The best fit and the $1 \sigma$ region in the $m_1 - m_2$ plane is shown in Fig. 8 for the “EG”-case for the background protons. The dependence of this result on the cosmological evolution and on the UHEC$\nu$ spectrum will be discussed in Ref. (Fodor et al., in prep.). Since this two-mass scenario has much less constraints the allowed region for the masses is larger than in the one-mass scenario.

5 Comparison with other studies

Numerical simulations of Z-burst cascades for $m_\nu \sim 1$ eV, taking into account all known extragalactic propagation effects, were performed by Yoshida et al. (1998). Based on case studies, local overdensities by factors ranging from $20 \div 10^3$ over the standard cosmological relic neutrino number density on a scale of 5 Mpc were argued to be necessary in order to get a successful description of the UHECR events and rate above the GZK cutoff without violating lower energy photon flux limits and without invoking inconceivable UHEC$\nu$ fluxes. For such large overdensities, most of the UHECRs from Z-bursts originate nearby and their attenua-
The presently observed ultrahigh energy region, over the one effects. Therefore, despite of the fact that by construction distances and suffer therefore much more from GZK attenuation however, may be mildered by a factor of 2000; Primack, priv. comm.). The case without remarkable density. Gravitational clustering is really too inefficient for neutrinos should be hidden even in background measured by EGRET (Sreekumar et al., 1998). One of the possibilities are sources whose surrounding is so dense that no ultrahigh energy photons can escape. It is an interesting question whether such conditions can be realized in BL Lacertae objects, a class of active galactic nuclei recently discussed as possible sources of the highest energy cosmic rays (Tinyakov and Tkachev, 2001). Alternatively, one may invoke top-down scenarios (Bhattacharjee and Sigl, 2000) for the sources of the highest energy cosmic neutrinos such as unstable superheavy relic particle decays (Gelmini and Kusenko, 2000).

6 Conclusions

I reviewed a recent comparison of the predicted spectrum from Z-bursts – resulting from the resonant annihilation of ultrahigh energy cosmic neutrinos with relic neutrinos – with the observed ultrahigh energy cosmic ray spectrum (Fodor et al., 2001a, in prep.). The mass of the heaviest relic neutrino turned out to be $m_{\nu} = 2.75^{+1.28}_{-1.02}$ eV for halo- and 0.26$^{+0.20}_{-0.14}$ eV for extragalactic-scenarios for the background protons. The second mass, with a lower bound of 0.06 eV on the 95% CL, is compatible with a hierarchical neutrino mass scenario with the largest mass suggested by the atmospheric neutrino oscillation. The above neutrino masses are in the range which can be explored by future laboratory experiments like the $\beta$ decay endpoint spectrum and the neutrino-less $\beta\beta$ decay (Päss and Weiler, 2001; Vissani, 2001; Farzan et al., 2001; Olsland and Vigdel, 2001; Czakon et al., 2001) or by simultaneous observations of the bursts of neutrinos and gravitational waves emitted during a stellar collapse (Arnaud et al., 2001). They compare also favourably with the upper limit $\sum_i m_{\nu_i} \leq 4.4$ eV found recently from a global cosmological analysis involving also the recent CMBR measurements (Wang et al., 2001), with a future sensitivity down to $\leq 0.3$ eV (Hu et al., 1998). We analysed a possible two-mass scenario and gave the corresponding confidence level region. The necessary UHEC$\nu$ flux was found to be consistent with present upper limits and detectable in the near future. Astrophysical sources of these ultrahigh energy cosmic neutrinos should be hidden even in $\gamma$ rays.

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References

Abe, K. et al., hep-ex/9908033
Abe, K. et al., OPAL PN299, unpublished.
Abreu, P. et al., Nucl. Phys. B 444, 3, 1995.
Akers, R. et al., Z. Phys. C 63, 181, 1994.

Arnaud, N. et al., Z. Phys. C 63, 181, 1994.

Ave, M. et al., Phys. Rev. Lett. 55, 2244, 2000.

Bahcall, J.N. and Waxman, E., Astrophys. J. 542, 543, 2000.

Bahcall, J.N. and Waxman, E., Phys. Rev. D 64 (2001) 023002.

Baltrusaitis, R.M. et al., Phys. Rev. D 31, 2192, 1985.

Barwick, S., www.ps.uci.edu/~amanda

Berezinsky, V.S. and Zatsepin, G.T., Phys. Lett. B 28 (1969) 423.

Berezinsky, V.S. and Zatsepin, G.T., Sov. J. Nucl. Phys. 11 (1970) 111 [Yad. Fiz. 11 (1970) 200].

Berezinsky, V.S., in Proc. DUMAND Summer Workshops, Learned, J.G. (Ed.), Khabarovsk and Lake Baikal, 22-31 Aug 1979, Hawaii DUMAND Center, University of Hawaii, 1980, pp. 245-261.

Bertou, X. et al., Int. J. Mod. Phys. A15, 2181, 2000.

Bhattacharjee, P. and Sigl, G., Phys. Rept. 327, 109, 2000.

Biebel, O., private communication.

Bird, D.J. et al., Phys. Rev. Lett. 71, 3401, 1993.

Bird, D.J. et al., Astrophys. J. 424, 491, 1994.

Bird, D.J. et al., Astrophys. J. 441, 144, 1995.

Blanco-Pillado, J.J. et al., Phys. Rev. D 61, 123003, 2000.

Buskulic, D. et al., Z. Phys. C 66, 355, 1995.

Capelle, K.S. et al., Astropart. Phys. 8, 321, 1998.

Czakon, M. et al., hep-ph/0110166.

da Costa, L.N. et al., Astrophys. J. 468, L5, 1996.

Dekel, A. et al., Astrophys. J. 522, 1, 1999.

Efimov, N.N. et al., in Proc. of the Astrophysical Aspects of the Most Energetic Cosmic Rays (World Scientific, Singapore, 1991).

Engel, R. and Stanev, T. Phys. Rev. D 64 (2001) 093010.

Fargion, D., Mele, B. and Sigl, G., Astrophys. J. 517, 725, 1999.

Fargion, D. et al., astro-ph/0102426.

Farzan, Y. et al., Nucl. Phys. B 612 (2001) 59.

Fodor, Z. and Katz, S.D., Phys. Rev. D 63, 023002, 2001.

Fodor, Z. and Katz, S.D. Phys. Rev. Lett. 86, 3224, 2001.

Fodor, Z., Katz, S.D., and Ringwald, A., hep-ph/0105064

Gandhi, R., Nucl. Phys. Proc. Suppl. 91 (2000) 453.

Gelmini, G. and Kusenko, A., Phys. Rev. Lett. 82, 5202, 1999.

Gelmini, G. and Kusenko, A., Phys. Rev. Lett. 84 (2000) 1378.

Gorham, P.W. et al., astro-ph/0102435

Greisen, K., Phys. Rev. Lett. 16, 748, 1966.

Groom, D.E. et al., Eur. Phys. J. C 15, 1, 2000.

Guérard, C.K., Nucl. Phys. Proc. Suppl. 75A, 380, 1999.

Hu, W. et al., Phys. Rev. Lett. 80 (1998) 5255.

Kieda, D. et al., in Proceedings of the 26th International Cosmic Ray Conference, Salt Lake, 1999.

Kneller, J.P. et al., Phys. Rev. D 64 (2001) 123506.

Learned, J.G. and Mannheim, K., Ann. Rev. Nucl. Part. Sci. 50 (2000) 679.

Lawrence, M.A. et al., J. Phys. G 17, 773, 1991.

Ma, C.P., astro-ph/9904001.

Mannheim, K. et al., Phys. Rev. D 63 (2001) 023003.

McKellar, B.H. et al., hep-ph/0106123.

Ormes, J.F. et al., in Proc. of the 25th International Cosmic Ray Conference, Potchefstrom, 1997.

Oslund, P. and Vigdel, G., Phys. Lett. B 520 (2001) 143

Päs, H. and Weiler, T.J., Phys. Rev. D 63 (2001) 113015.

Primack, J.R. and Gross, M.A., astro-ph/0007165.

Primack, J.R., private communication.

Protheroe, R.J. and Johnson, P.A., Astrophys. J. 500 (1996) 253 [Erratum-ibid. 5 (1996) 215].

Protheroe, R.J., Nucl. Phys. Proc. Suppl. 77 (1999) 465.

Roulet, E., Phys. Rev. D 47, 5247, 1993.

Seckel, D. et al., in Proc. 27th International Cosmic Ray Conference, Hamburg, 2001, pp. 1137-1140.

Sigl, G., private communication

Sreekumar, P. et al., Astrophys. J. 494, 523 (1998).

Takeda, M. et al., Phys. Rev. Lett. 81, 1163, 1998.

Takeda, M. et al., astro-ph/9902239.

Tinyakov, P.G. and Tkachev, I.I., astro-ph/0102476.

Wang, X., Tegmark, M., and Zaldarriaga, M., astro-ph/0105091.

Waxman, E., Astrophys. J. 452, L1, 1995.

Waxman, E., astro-ph/9804023.

Waxman, E. and Bahcall, J.N., Phys. Rev. D 59 (1999) 023002.

Weiler, T., Phys. Rev. Lett. 49, 234, 1982.

Weiler, T.J., Astropart. Phys. 11, 303, 1999; 12, 379, 2000 (Err.).

Vissani, F., Nucl. Phys. Proc. Suppl. 100 (2000) 273.

Yoshida, S. and Teshima, M. Prog. Theor. Phys. 89 (1993) 833.

Yoshida, S. et al., Astrophys. J. 479 (1997) 547.

Yoshida, S., Sigl, G., and Lee, S., Phys. Rev. Lett. 81, 5505, 1998.

Yoshida, S. et al., in Proc. 27th International Cosmic Ray Conference, Hamburg, 2001, pp. 1142-1145.

Zatsepin, G.T. and Kuzmin, V.A., Pisma Zh. Eksp. Teor. Fiz. 4, 114, 1966.