HOW TO DETECT THE COSMIC NEUTRINO BACKGROUND?

A. RINGWALD
Deutsches Elektronen-Synchrotron DESY,
Notkestraße 85,
D-22607 Hamburg, Germany
E-mail: andreas.ringwald@desy.de

A measurement of the big bang relic neutrinos would open a new window to the early universe. We review various possibilities to detect this cosmic neutrino background and substantiate the assertion that – apart from the rather indirect evidence to be gained from cosmology and large-scale structure formation – the annihilation of ultrahigh energy cosmic neutrinos with relic anti-neutrinos (or vice versa) on the Z-resonance is a unique process having sensitivity to the relic neutrinos, if a sufficient flux at $E_{\nu_i} = M_Z^2/(2m_{\nu_i}) = 4 \cdot 10^{22}$ eV $(0.1 \text{ eV}/m_{\nu_i})$ exists. The associated absorption dips in the ultrahigh energy cosmic neutrino spectrum may be searched for at forthcoming neutrino and air shower detectors. The associated protons and photons may have been seen already in form of the cosmic ray events above the Greisen-Zatsepin-Kuzmin cutoff.

1. The Cosmic Neutrino Background

Standard big bang cosmology predicts a diffuse background of free photons and neutrinos. The measured cosmic microwave background (CMB) radiation supports the applicability of standard cosmology back to photon decoupling which occurred approximately three hundred thousand years after the big bang. The predicted neutrinos from the elusive cosmic neutrino background ($C\nu B$), on the other hand, have decoupled when the universe had a temperature of one MeV and an age of just one second. Thus, a measurement of the $C\nu B$ would open a new window to the early universe. Its properties are tightly related to the properties of the CMB and are therefore to be considered as rather firm predictions. In the absence of appreciable lepton asymmetries one predicts, for example,

\begin{align}
\langle |\vec{p}_{\nu_i}| \rangle_0 &= \langle |\vec{p}_{\bar{\nu}_i}| \rangle_0 = 3.2 \cdot (4/11)^{1/3} T_\gamma 0 = 5 \cdot 10^{-4} \text{ eV}, \\
\langle n_{\nu_i} \rangle_0 &= \langle n_{\bar{\nu}_i} \rangle_0 = (3/22) \langle n_\gamma \rangle_0 = 56 \text{ cm}^{-3}
\end{align}

Talk presented at the Workshop on Strong and Electroweak Matter (SEWM 2002), October 2-5, 2002, Heidelberg, Germany.
\[ \Omega_{C\nu B} = 2 \sum_{i=1}^{3} m_{\nu_i} \langle n_{\nu_i} \rangle_0 / \rho_c = (1 \cdot 10^{-3} / h^2) \sum_{i=1}^{3} m_{\nu_i} / (0.1 \text{ eV}), \]  

for today's average 3-momentum \( \langle |\vec{p}_{\nu_i}| \rangle_0 \) and number density \( \langle n_{\nu_i} \rangle_0 \) of light \( (m_{\nu_i} \ll 1 \text{ MeV}) \) neutrino species \( i \), and today's relative contribution \( \Omega_{C\nu B} \) to the critical energy density of the universe, in terms of today's CMB temperature \( T_{\gamma,0} \) and photon number density \( \langle n_{\gamma} \rangle_0 \). The relic neutrino number density is comparable to the one of the microwave photons. However, since neutrinos interact only weakly, the relic neutrinos have not yet been detected directly in laboratory experiments. Indeed, the average energy of the relic neutrinos is so small, that charged or neutral current cross-sections for incoherent scattering off ordinary matter are negligibly small,

\[ \sigma_{\nu_i N} \simeq G_F^2 \langle E_{\nu_i} \rangle_0^2 / \pi \simeq 2 \cdot 10^{-58} \text{ cm}^2 \left( m_{\nu_i} / (0.1 \text{ eV}) \right)^2, \]

leading to absurdly small event rates, even for kiloton \((N_T \sim 10^{33})\) targets,

\[ R_{\nu_i}^{ic} = N_T \langle n_{\nu_i} \rangle_0 \langle |\vec{v}_{\nu_i}| \rangle_0 \sigma_{\nu_i N} \simeq 5 \cdot 10^{-8} \text{ yr}^{-1} \left( N_T / 10^{33} \right) \left( m_{\nu_i} / (0.1 \text{ eV}) \right). \]

Apart from the rather indirect evidence for the \( C\nu B \) to be gained from cosmology and large-scale structure formation\(^1\), which are mainly sensitive to \( \Omega_{C\nu B} \) \((3)\), two more direct possibilities have been pointed out in the literature and will be outlined in this short review: \( i) \) The coherent elastic scattering of the flux of relic neutrinos off target matter in a terrestrial detector (flux detection, Sect. 2). \( ii) \) The scattering of ultrahigh energy particles (accelerator beams or cosmic rays) off the relic neutrinos as a target (target detection, Sect. 3).

Throughout this review, we will take for granted the oscillation interpretation of atmospheric, solar, and reactor neutrino data\(^2\). This, together with the upper mass limit from tritium \( \beta \) decay\(^3\), implies that the heaviest neutrino has a mass between \( 0.04 \text{ eV} < m_{\nu_3} < 2.2 \text{ eV} \). An even stronger – albeit more model-dependent – upper bound \( m_{\nu_3} < 0.8 \text{ eV} \) is obtained from large-scale structure formation\(^1\). Such light neutrinos have a very large free streaming length. Therefore, gravitational clustering of relic neutrinos on the galactic scale can be completely neglected, and we base our estimates for terrestrial experiments on the standard cosmological value \((2)\). Moreover, unclustered, i.e. uniform, enhancements of \( \langle n_{\nu_i} + n_{\bar{\nu}_i} \rangle_0 \) due to possible neutrino degeneracies can also be safely neglected because of recent strong bounds on the latter arising from an analysis of big bang nucleosynthesis, taking into account flavor equilibration due to neutrino oscillations before \( n/p \) freeze-out\(^4\). Under these conditions, i.e. with no
appreciable enhancements of the relic neutrino number densities in comparison to the standard values \( \rho_{\nu} \), we shall conclude, in accordance with Weiler\(^5\), that the annihilation of ultrahigh energy cosmic neutrinos with relic anti-neutrinos (or vice versa) on the \( Z \)-resonance (cf. Fig. 1 (left)) is the unique process having sensitivity to the relic neutrinos, if a sufficient flux at \( E_{\nu}^{\text{res}} = M_Z^2/(2m_{\nu}) = 4 \cdot 10^{22} \text{ eV} \) \( (0.1 \text{ eV}/m_{\nu}) \) exists.

2. Flux Detection of the \( C\nu\beta \)

The average momentum (1) of relic neutrinos corresponds to a de Broglie wavelength of macroscopic dimension, \( \langle \lambda_{\nu} \rangle_0 = 2\pi/(\langle |\vec{p}_{\nu}| \rangle_0 = 0.23 \text{ cm} \). Therefore, one may envisage scattering processes in which many target atoms act coherently\(^6\) over a macroscopic volume \( \langle \lambda_{\nu} \rangle_0^3 \), so that the reaction rate becomes proportional to the square of the number of target atoms in that volume, \( N_T^2 \), in contrast to the incoherent case (5). Furthermore, in case of coherent scattering, it may be possible to observe the scattering amplitude itself\(^7\), which is linear in \( G_F \): \( \mathcal{M}_{\nu_i} \sim N_T G_F m_{\nu_i} \). However, in this case one needs a large lepton asymmetry for a non-negligible effect.

A practical scheme to detect the flux of the \( C\nu\beta \) by an exploitation of the above coherent \( G_F^2 \) effect is based on the fact that a test body of density \( \rho_T \) at earth will experience a neutrino wind force through random neutrino
scattering events, corresponding to an acceleration \(8^9\)

\[
\alpha_T = N_A^2 \rho_T (\lambda_\nu/\rho_\nu) \langle n_\nu \rangle_{0} v_{\text{earth}} \sigma_{\nu, N} \langle |\vec{p}_\nu| \rangle_0
\]

\[
\simeq 4 \cdot 10^{-29} \text{ cm/s}^2 (\rho_T/(g \text{ cm}^{-3})) (v_{\text{earth}}/(10^{-3} c)) (m_\nu/(0.1 \text{ eV}))^2,
\]

where \(N_A\) is Avogadro’s constant and \(v_{\text{earth}}\) is the velocity of the earth relative to the CMB. Expression (6) applies only for Dirac neutrinos. For Majorana neutrinos, the acceleration is suppressed by a further factor of \((v_{\text{earth}}/c)^2(1)\) in case of an unpolarized (polarized) target. Therefore, we conclude that this effect is still far from observability. At present, the smallest measurable acceleration is \(\gtrsim 10^{-13} \text{ cm/s}^2\) through conventional Cavendish-type torsion balances. Possible improvements to a sensitivity of \(\gtrsim 10^{-23} \text{ cm/s}^2\) have been proposed \(^8\) (cf. Fig. 1 (right)). However, this is still way off the prediction (6), unless one invokes a very unlikely enhancement of the local relic neutrino number density by a factor of \(10^6\).

3. Target Detection of the C\(\nu\)B

Let us consider next the idea to take advantage of the fact that at center-of-mass (cm) energies below the \(W\)- and \(Z\)-resonances the neutrino cross-sections are rapidly growing with energy. Correspondingly, one may envisage the possibility to exploit a flux of ultrahigh energy particles – either from accelerator beams or from cosmic rays – for scattering on the C\(\nu\)B. However, the attainable cm energies,

\[
\sqrt{s} = \sqrt{2 m_\nu E_{\text{beam}}} = 0.4 \text{ MeV} \left( m_\nu/(0.1 \text{ eV}) \right)^{1/2} \left( E_{\text{beam}}/(1 \text{ TeV}) \right)^{1/2},
\]

at forthcoming accelerator beams such as TESLA/LHC/VLHC, with beam energies \(E_{\text{beam}}\) of 0.5/7/10 TeV, are so low, that the cross-sections for such interactions are still quite small,

\[
\sigma_{\nu, \text{beam}} \simeq G_F^2 s/\pi \simeq 3 \cdot 10^{-46} \text{ cm}^2 \left( m_\nu/(0.1 \text{ eV}) \right) \left( E_{\text{beam}}/(1 \text{ TeV}) \right),
\]

leading to a terribly small scattering rate of \(^{10}\)

\[
R_{\nu, \text{beam}} \simeq 4 \cdot 10^{-12} \text{ yr}^{-1} \left( I/\dot{A} \right) \left( L/10 \text{ km} \right) \left( m_\nu/(0.1 \text{ eV}) \right) \left( E_{\text{beam}}/(1 \text{ TeV}) \right),
\]

for a beam of length \(L\) and current \(I\). Thus, there is little hope for detection of the C\(\nu\)B using terrestrial accelerator beams in the foreseeable future.

Let us finally consider cosmic rays. Ultrahigh energy cosmic rays have been seen by air shower observatories such as AGASA\(^{11}\), Fly’s Eye\(^{12}\), Haverah Park\(^{13}\), HiRes\(^{14}\), and Yakutsk\(^{15}\), up to energies \(E_{\text{cr}} \sim 10^{20} \text{ eV}\), corresponding to cm energies

\[
\sqrt{s} = \sqrt{2 m_\nu E_{\text{beam}}} = 4 \text{ GeV} \left( m_\nu/(0.1 \text{ eV}) \right)^{1/2} \left( E_{\text{cr}}/(10^{20} \text{ eV}) \right)^{1/2}.
\]
The latter are not too far away from the $W$- and $Z$-resonances, at which the electroweak cross-sections get sizeable. Indeed, it has been pointed out long ago by Weiler, that the resonant annihilation of ultrahigh energy cosmic neutrinos with relic (anti-)neutrinos on the $Z$-boson appears to be a unique process having sensitivity to the $C\nu B$. On resonance, $E_{\nu}^{\text{res}} = M_Z^2/(2m_\nu) = 4 \cdot 10^{22}$ eV (0.1 eV/$m_\nu$), the corresponding cross-section is enhanced by several orders of magnitudes,

$$\langle \sigma_{\text{ann}} \rangle = \int ds/M_Z^2 \sigma_{\nu \bar{\nu}}(s) = 2\pi\sqrt{2}G_F \simeq 4 \cdot 10^{-32} \text{ cm}^2,$$

leading to a “short” mean free path $\ell_{\nu,0} = (\langle m_\nu \rangle_0 \langle \sigma_{\text{ann}} \rangle)^{-1} \simeq 1.4 \cdot 10^5$ Mpc which is “only” about $48 \, h$ times the Hubble distance. This corresponds to an annihilation probability for ultrahigh energy neutrinos from cosmological distances on the $C\nu B$ of $2 \, h^{-1} \%$, neglecting cosmic evolution effects. The signatures of annihilation might be i) absorption dips in the ultrahigh energy cosmic neutrino spectrum at the resonant energies and ii) emission features (Z-bursts) as protons (or photons) (cf. Fig. 1 (left)) above the predicted Greisen-Zatsepin-Kuzmin-cutoff at $E_{\text{GZK}} \simeq 4 \cdot 10^{19}$ eV.

In fact, since Weiler’s 1982 proposal of absorption dips, a (significant(?)) number of cosmic rays with energies above $E_{\text{GZK}}$ has been accumulated by air shower observatories (cf. Fig. 2 (left)). This presents

\[\text{For earlier and related suggestions, see Ref.}^{16} \text{ and Ref.}^{17}, \text{ respectively.}\]
a puzzle, since these cosmic rays of most probably extragalactic origin\(^\text{b}\) should show a pronounced depletion above \(E_{\text{GZK}}\) (cf. Fig. 2 (left)), since nucleons with super-GZK energies have a short energy attenuation length of about 50 Mpc due to inelastic interactions with the CMB. Ultrahigh energy neutrinos produced at cosmological distances, on the other hand, can reach the GZK zone unattenuated and their resonant annihilation on the relic neutrinos could just result in the observed cosmic rays beyond \(E_{\text{GZK}}\).

The energy spectrum of the highest energy cosmic rays depends critically on the neutrino mass if they are indeed produced via Z-bursts\(^{19,21,22,23}\). From a quantitative comparison of the predicted spectrum with the observed one (cf. Fig. 2 (left)), one can therefore infer the required mass of the heaviest neutrino\(^{22}\). The value of the neutrino mass obtained in this way is fairly robust against variations in presently unknown quantities, such as the amount of the universal radio background and the extragalactic magnetic field, within their anticipated uncertainties. It turns out to lie in the range \(0.08 \text{ eV} \leq m_{\nu_3} \leq 1.3 \text{ eV}\) at the 68\% confidence level, which compares favourably with the present knowledge coming from oscillations, tritium beta decay\(^3\), and neutrinoless double beta decay\(^{24}\). This range narrows down considerably if a particular universal radio background is assumed, e.g. to \(0.08 \text{ eV} \leq m_{\nu_3} \leq 0.40 \text{ eV}\) for a large one.

The required ultrahigh energy cosmic neutrino fluxes (cf. Fig. 2 (right)) should be observed in the near future by existing neutrino telescopes, such as AMANDA and RICE, and by cosmic ray air shower detectors currently under construction, such as the Pierre Auger Observatory. Otherwise the Z-burst scenario for the origin of the highest-energy cosmic rays will be ruled out. The required neutrino fluxes are enormous. If such tremendous fluxes of ultrahigh energy neutrinos are indeed found, one has to deal with the challenge to explain their origin. It is fair to say, that at the moment no convincing astrophysical sources are known which meet the requirements of the Z-burst scenario, i.e. which accelerate protons at least up to \(10^{23}\) eV, are opaque to primary nucleons, and emit secondary photons only in the sub-MeV region\(^{25}\). However, even if the ultrahigh energy cosmic neutrino flux turns out to be too small for the above Z-burst scenario to be realized, a far future precision search for absorption dips in the resonant region\(^e\) –

\(^{b}\)Plausible astrophysical sources for those energetic particles are at cosmological distances.

\(^{e}\)Assuming that \(m_{\nu_3}\) is then already known from laboratory experiments.
presumably beyond the sensitivity of e.g. the projected Extreme Universe Space Observatory (EUSO) – may still reveal the existence of the $C\nu B$.

Acknowledgments

I would like to thank Z. Fodor and S. D. Katz for the nice collaboration on the Z-burst scenario and a careful reading of the manuscript.

References

1. W. Hu, D. J. Eisenstein and M. Tegmark, Phys. Rev. Lett. 80, 5255 (1998); O. Elgaroy et al., Phys. Rev. Lett. 89, 061301 (2002). S. Hannestad, arXiv:astro-ph/0205223.
2. Y. Fukuda et al. [Super-Kamiokande Collaboration], Phys. Rev. Lett. 81, 1562 (1998); S. Fukuda et al. [Super-Kamiokande Collaboration], Phys. Rev. Lett. 86, 5651 (2001); Q. R. Ahmad et al. [SNO Collaboration], Phys. Rev. Lett. 87, 071301 (2001); K. Eguchi et al. [KamLAND Collaboration], http://www.awa.tohoku.ac.jp/KamLAND/first_results/KamLAND_PRL.ps
3. C. Weinheimer et al., Phys. Lett. B 460, 219 (1999); V. M. Lobashev et al., Phys. Lett. B 460, 227 (1999).
4. C. Lunardini and A. Y. Smirnov, Phys. Rev. D 64, 073006 (2001); A. D. Dolgov, S. H. Hansen, S. Pastor, S. T. Petcov, G. G. Raffelt and D. V. Semikoz, Nucl. Phys. B 632, 363 (2002). Y. Y. Wong, Phys. Rev. D 66, 025015 (2002); K. N. Abazajian, J. F. Beacom and N. F. Bell, Phys. Rev. D 66, 013008 (2002).
5. T. J. Weiler, Phys. Rev. Lett. 49, 234 (1982); in: Neutrino Mass and Gauge Structure of Weak Interactions, Telemark, USA, 1982, pp. 60-75; Astrophys. J. 285, 495 (1984).
6. B. F. Shvartsman, V. B. Braginsky, S. S. Gershtein, Y. B. Zeldovich and M. Y. Khlopov, JETP Lett. 36, 277 (1982); P. F. Smith and J. D. Lewin, Phys. Lett. B 127, 185 (1983). Acta Phys. Polon. B 15, 1201 (1984); Acta Phys. Polon. B 16, 837 (1985); Phys. Rept. 187, 203 (1990); G. Tupper, B. Müller, J. Rafelski and M. Danos, Phys. Rev. D 35, 394 (1987); I. Ferreras and I. Wasserman, Phys. Rev. D 52, 5459 (1995); C. C. Speake and J. Leon, Class. Quant. Grav. 13, A207 (1996).
7. L. Stodolsky, Phys. Rev. Lett. 34, 110 (1975) [Erratum-ibid. 34, 508 (1975)]. N. Cabibbo and L. Maiani, Phys. Lett. B 114, 115 (1982); P. Langacker, J. P. Leveille and J. Sheiman, Phys. Rev. D 27, 1228 (1983).
8. C. Hagmann, in: Conference on particle physics and the early universe (COSMO 98), Asilomar, USA, 1998, pp. 460-463, arXiv:astro-ph/9902102; presented at: American Physical Society (APS) Meeting of the Division of Particles and Fields (DPF 99), Los Angeles, USA, 1999, arXiv:astro-ph/9905258.
9. G. Duda, G. Gelmini and S. Nussinov, Phys. Rev. D 64, 122001 (2001).
10. B. Müller, in: 10th Workshop on Particles and Nuclei: Neutrino Physics,
11. M. Takeda et al., Phys. Rev. Lett. 81, 1163 (1998).
12. D. J. Bird et al. [HIRES Collaboration], Phys. Rev. Lett. 71, 3401 (1993); Astrophys. J. 424, 491 (1994); Astrophys. J. 441, 144 (1995).
13. M. A. Lawrence, R. J. Reid and A. A. Watson, J. Phys. G 17, 733 (1991); M. Ave, J. A. Hinton, R. A. Vazquez, A. A. Watson and E. Zas, Phys. Rev. Lett. 85, 2244 (2000).
14. D. Kieda et al., in Proceedings of the 26th International Cosmic Ray Conference, Salt Lake, 1999; T. Abu-Zayyad et al. [High Resolution Fly’s Eye Collaboration], arXiv:astro-ph/0208243.
15. N.N. Efimov et al., in Proc. of the Astrophysical Aspects of the Most Energetic Cosmic Rays (World Scientific, Singapore, 1991).
16. J. Bernstein, M. Ruderman and G. Feinberg, Phys. Rev. 132, 1227 (1963); B. P. Konstantinov and G. E. Kovalov, J. Exp. Theor. Phys. 19, 992 (1964); R. Cowsk, Y. Pal and S. N. Tandon, Phys. Lett. 13, 265 (1964); T. Hara and H. Sato, Prog. Theor. Phys. 64, 1089 (1980); ibid. 65, 477 (1981).
17. R. Wigmans, arXiv:astro-ph/0205360; E. A. Paschos and O. Lalakulich, arXiv:astro-ph/0206273; S. Davidson, S. Forte, P. Gambino, N. Rius and A. Strumia, JHEP 0202, 037 (2002).
18. E. Roulet, Phys. Rev. D 47, 5247 (1993). S. Yoshida, H. Y. Dai, C. C. Jui and P. Sommers, Astrophys. J. 479, 547 (1997).
19. D. Fargion, B. Mele and A. Salis, Astrophys. J. 517, 725 (1999); T. J. Weiler, Astropart. Phys. 11, 303 (1999). S. Yoshida, G. Sigl and S. j. Lee, Phys. Rev. Lett. 81, 5505 (1998).
20. K. Greisen, Phys. Rev. Lett. 16, 748 (1966); G. T. Zatsepin and V. A. Kuzmin, JETP Lett. 4, 78 (1966).
21. H. Pas and T. J. Weiler, Phys. Rev. D 63, 113015 (2001).
22. Z. Fodor, S. D. Katz and A. Ringwald, Phys. Rev. Lett. 88, 171101 (2002); JHEP 0206, 046 (2002).
23. G. Gelmini and G. Varieschi, arXiv:hep-ph/0201273. S. Singh and C. P. Ma, arXiv:astro-ph/0208419.
24. H. V. Klapdor-Kleingrothaus et al., Eur. Phys. J. A 12, 147 (2001). H. V. Klapdor-Kleingrothaus, A. Dietz, H. L. Harney and I. V. Krivosheina, Mod. Phys. Lett. A 16, 2409 (2002).
25. O. E. Kalashev, V. A. Kuzmin, D. V. Semikoz and G. Sigl, Phys. Rev. D 65, 103003 (2002). P. Chen, T. Tajima and Y. Takahashi, Phys. Rev. Lett. 89, 161101 (2002); D. S. Gorbunov, P. G. Tinyakov and S. V. Troitsky, arXiv:astro-ph/0206385.