Possible detection of relic neutrinos and determination of their mass: quantitative analysis

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(October 5, 2018)

We consider the possibility that a large fraction of the ultrahigh energy cosmic rays (UHECRs) are decay products of Z bosons which were produced in the scattering of ultrahigh energy cosmic neutrinos (UHECνs) on cosmological relic neutrinos (Rνs). We compare the observed UHECR spectrum with the one predicted in the above Z-burst scenario and determine the mass of the heaviest Rν as well as the necessary UHECν flux via a maximum likelihood analysis.

I. INTRODUCTION

Big-bang cosmology predicts the existence of the cosmic microwave background radiation (CMBR) and a similar background of Rνs with an average number density of \( n_{\nu} \approx 56 \) cm\(^{-3}\) per light neutrino species \( \nu \) (\( m_{\nu} < 1 \) MeV). However, the Rνs have not been detected until now.

A possibility for their detection was discussed some time ago: the UHECν spectrum should have absorption dips at energies \( E_{\nu} \approx M_Z^2/(2m_{\nu}) = 4.2 \cdot 10^{21} \) eV (1 eV/m\(_{\nu}\)) due to resonant annihilation with the Rνs into Z bosons of mass \( M_Z \). Recently it was realized that the same annihilation mechanism might already be visible in the UHECR spectrum at energies above the predicted Greisen-Zatsepin-Kuzmin (GZK) cutoff around \( 4 \cdot 10^{19} \) eV. It was argued that the UHECRs above the GZK cutoff are mainly protons from Z decay.

This hypothesis was discussed in several papers \cite{1-3}. We report here on our recent quantitative investigation of the Z-burst scenario, where we have determined the mass of the heaviest Rν as well as the necessary UHECν flux via a maximum likelihood analysis \cite{2-3}.

Our comparison of the Z-burst scenario with the observed UHECR spectrum was done in four steps. First, we determined the probability of Z production as a function of the distance from Earth. Secondly, we exploited collider experiments to derive the energy distribution of the produced protons in the lab system. Thirdly, we considered the propagation of the protons, i.e. we determined their energy losses due to pion and \( e^+e^- \) production through scattering on the CMBR and due to their redshift. The last step was the comparison of the predicted and observed spectra and the extraction of the mass of the Rν and the necessary UHECν flux.

II. Z-BURST SPECTRUM

Our prediction of the contribution of protons from Z-bursts to the UHECR spectrum, for degenerate \( \nu \) masses \( (m_{\nu} \approx m_{\nu}) \), can be summarized as

\[
j(E, m_{\nu}) = I \cdot F_Z^{-1} \cdot \int_0^\infty \int_0\infty \int_0\infty dE_p \int dr \int d\epsilon \partial P(r, E_p, E)/\partial E \tag{1}
\]

\[
F_{\nu}(E_{\nu}, r)\sigma(\epsilon)Q(E_p)\left(-\partial P(r, E_p, E)/\partial E\right),
\]

where the total time and angle integrated detector area \( I \) and the normalization factor \( F_Z \), which is proportional to the sum of the \( \nu \) fluxes at centre-of-mass (CM) energy \( M_Z \), are determined later by the comparison with the UHECR data. \( E \) is the energy of the protons arriving at Earth. Further important ingredients in our prediction are: the UHECν fluxes \( F_{\nu}(E_{\nu}, r) \) at the resonant energy \( E_{\nu} \approx E_{\nu}^{res} \) and at distance \( r \) to Earth, the number density \( n_{\nu}(r) \) of the Rνs, the Z production cross section \( \sigma(\epsilon) \) at CM energy \( \epsilon = \sqrt{2m_{\nu}E_{\nu}} \), the energy distribution \( Q(E_p) \) of the produced protons 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 three building blocks, \( \sigma \), \( Q \), and \( P \), are very well determined. At LEP and SLC millions of Z bosons were produced and their decays analyzed with extreme high accuracy. We used existing published \cite{10,11,12} and some improved unpublished \cite{21,22} data to determine the proton momentum distribution \( Q(E_p) \). Due to the large statistics, the uncertainties of our analysis related to Z decay turned out to be negligible. Similarly, the CMBR is known to a high accuracy. It plays the key role in the determination of the probability \( P(r, E_p, E) \) \cite{21,22}, which takes into account the fact that protons of extragalactic (EG) origin and energies above \( \approx 4 \cdot 10^{19} \) eV lose a large fraction of their energies \cite{10,11,12} 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 two of the present authors \cite{22}, was an indispensable tool in our quantitative analysis.

Less accurately known in Eq. \cite{10} are the first two ingredients, the flux of UHECνs, \( F_{\nu}(E_{\nu}, r) \), and the neutrino number density \( n_{\nu}(r) \).
The former was assumed to have the form \( F_{\nu_{\nu}}(E_{\nu_{\nu}}, r) = F_{\nu_{\nu}}(E_{\nu_{\nu}}, 0)(1 + z)^{\alpha} \), where \( z \) is the redshift and where \( \alpha \) characterizes the source evolution (see also Fig. 1). The flux at Earth, \( F_{\nu_{\nu}}(E_{\nu_{\nu}}, 0) \), has been determined by the fit to the UHECR data. In our analysis we went up to distances \( R_0 \) (cf. Fig. 1) corresponding to redshift \( z = 2 \) (cf. [23]), and uncertainties of the expansion rate [24] were included.

The neutrino number density \( n_{\nu} \) has been treated in the following way. For distances below 100 Mpc we varied the shape of the \( n_{\nu}(r) \) distribution between the homogeneous case and that of \( m_{\text{tot}}(r) \), the total mass distribution obtained from peculiar velocity measurements [25]. In this way we took into account that the density distribution of \( R_0 \) as hot dark matter (DM) follows the big-bang cosmology prediction, \( n_{\nu_{\nu}} = 56 \cdot (1 + z)^{3} \text{ cm}^{-3} \).

### III. Determination of \( M_{\nu} \) and UHECR Flux

We compared the predicted spectrum [2] of protons from Z-bursts with the observed UHECR spectrum (cf. Fig. 1). Our analysis included UHECR data of AGASA [26,27], Fly’s Eye [28–30], Haverah Park [31,32], and HIRES [33]. Due to normalization difficulties we did not use the Yakutsk [34] results.

The predicted number of UHECR events in a bin was taken as

\[
N(i) = \int_{E_{i}}^{E_{i+1}} dE \left[ A \cdot E^{-\beta} + F_{Z} \cdot j(E, m_{\nu}) \right], \tag{2}
\]

where \( E_{i} \) is the lower bound of the \( i \)th energy bin. The first term is the usual power-law behavior, which describes the data well for smaller energies [26,27]. For this term we studied two possibilities. In the first case we assumed that the power part is produced in our galaxy. Thus no GZK effect was included for it (“halo”). In the second – in some sense more realistic – case we assumed that the protons come from uniformly distributed, EG sources and suffer from the GZK cutoff (”EG”). In this case the simple power-law-like term is modified, by taking into account the probability \( P(r, E_{p}, E) \), and falls off around \( 4 \cdot 10^{19} \text{ eV} \) (see Fig. 1). The second term of the flux in Eq. (4) corresponds to the spectrum of the Z-bursts, Eq. (1). A and \( F_{Z} \) are normalization factors. Note that the following implicit assumptions have been made through the form of Eq. (4): i) We have assumed (and later checked) that the UHE photons from Z-bursts can be neglected. ii) We have assumed that there are no significant additional primary UHE proton fluxes beyond the extrapolation of the above power-law. This constraint will be relaxed in a future publication [35].

The expectation value for the number of events in a bin is given by Eq. (4). To determine the most probable value for \( m_{\nu} \), we used the maximum likelihood method and minimized [36] the \( \chi^{2}(\beta, A, F_{Z}, m_{\nu}) \),

\[
\chi^{2} = \sum_{i=18.5}^{26.0} 2 \left[ N(i) - N_{o}(i) + N_{o}(i) \ln(N_{o}(i)/N(i)) \right], \tag{3}
\]

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

In our fitting procedure we had four parameters: \( \beta, A, F_\nu, m_\nu \). The minimum of the \( \chi^2(\beta, A, F_\nu, m_\nu) \) function is \( \chi^2_{\text{min}} \) at \( m_{\nu,\text{min}} \), which is the most probable value for the mass, whereas \( \chi^2(\beta', A', F_\nu', m_\nu') = \chi^2_{\text{min}} + 1 \) gives the 1\( \sigma \) (68%) confidence interval for \( m_\nu \). Here \( \beta', A', F_\nu' \) are defined in such a way that the \( \chi^2(\beta, A, F_\nu, m_\nu) \) function is minimized in \( \beta, A \) and \( F_\nu \) at fixed \( m_\nu \).

Qualitatively, our analysis can be understood in the following way. In the Z-burst scenario a small \( R_\nu \) 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 \( E_\nu \). In this way the shape of the detected energy \( (E) \) spectrum determines the masses of the \( R_\nu \). The sum of the necessary UHEC\( \nu \) fluxes was then determined from the obtained normalization \( F_\nu \).

Our best fits to the observed data can be seen in Fig. 1, for evolution parameter \( \alpha = 1 \). We found a neutrino mass of \( 2.34^{+1.29}_{-0.84}(3.74) \text{ eV} \) for the “halo”- and \( 0.26^{+0.20}_{-0.14}(0.22) \text{ eV} \) for the “EG”-case, respectively. 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% CL. The fits are rather good; for 21 non-vanishing bins and 4 fitted parameters they can be as low as \( \chi^2 = 15.1 \). We determined \( m_\nu \) for a wide range of cosmological source evolution \( (\alpha = 0 \pm 3) \) and Hubble parameter \( (H_0 = 0.64 \pm 0.78 \text{ km/sec/Mpc}) \) and observed only a moderate dependence on them. The results remain within the above error bars. We performed a Monte-Carlo analysis studying higher statistics. In the near future, Auger \cite{12} 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\( \nu \) flux at \( E_\nu^\text{res} \) has been obtained from our fit values of the normalization \( F_\nu \). We have summarized them in Fig. 2, together with some existing upper limits and projected sensitivities of present, near future and future observational projects. It is apparent that the flux determination depends much more on the evolution uncertainties than the mass determination. The necessary \( \nu \) flux appears to be well below present upper limits and is within the expected sensitivity of AMANDA, Auger, and OWL.

IV. COMPARISON WITH \( \Delta m^2_\nu \) FROM \( \nu \) OSCILLATIONS

One of the most attractive patterns for \( \nu \) 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 par-ticle. Using the mass difference of the atmospheric \( \nu \) oscillation for the heaviest mass \( 24 \), one obtains values between 0.03 and 0.09 eV. It is an intriguing feature of our result 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 \( \nu \) oscillation solution, the other two – muon and tau – by the atmospheric \( \nu \) oscillation solution, whereas the mass difference between the two groups is of the order of 1 eV. We studied this possibility, too. On our mass scales and resolution 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. 3 for the “EG”-case. The dependence of this result on the cosmological evolution and on the UHEC\( \nu \) spectrum will be discussed elsewhere \cite{35}. Since this two-mass scenario has much less constraints the allowed region for the masses is larger than in the one-mass scenario.

V. DIFFERENCES WITH RESPECT TO YOSHIDA ET AL. (1998)

Numerical simulations of Z-burst cascades for \( m_\nu \simeq 1 \text{ eV} \), taking into account all known EG propagation effects, were performed by Yoshida et al. \cite{36}. Based on
case studies, relative overdensities of RSs ranging from $20 \div 10^3$ 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 attenuation to the Earth can be neglected. In our case, with realistic overdensities $\leq 2 \div 3$ on scales $\leq 100$ Mpc, most of the UHECRs from Z-bursts originate from cosmological distances. Therefore, despite of the fact that by construction the overall rate of UHECRs from Z-bursts observed at Earth is the same in both investigations, the predicted spectra are quite different. No large overdensity is needed to reproduce the data. Note that the EG scenario is dominated not by the nearby Z-burst but by the pile-up of Z-burst protons due to the GZK effect (cf. Fig. 1).

VI. CONCLUSIONS

We reported on a comparison of the predicted spectrum of the Z-burst hypothesis with the observed UHECR spectrum [13]. The mass of the heaviest $\nu$ was found to be $m_\nu = 2.34^{+0.29}_{-0.54}$ eV for halo and $0.26^{+0.20}_{-0.14}$ eV for EG scenarios. The second mass, with a lower bound of 0.06 eV on the 95% CL, is compatible with a hierarchical $\nu$ mass scenario with the largest mass suggested by the atmospheric $\nu$ oscillation. The above $\nu$ masses are in the range which can be explored by future laboratory experiments like the $\beta$ decay endpoint spectrum and the $\nu$ less $\beta\beta$ decay [3,14]. They compare also favourably with the tau(?) neutrino mass range $0.04 \div 4.4$ eV found recently from a detailed analysis of the latest CMBR measurements [3]. 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.

ACKNOWLEDGMENTS

We thank S. Barwick, O. Biebel, S. Bludman, W. Buchm"uller, K. Mannheim, H. Meyer, W. Ochs, and K. Petrovay for useful discussions. We thank the OPAL collaboration for their unpublished results on hadronic Z decays. This work was partially supported by Hungarian Science Foundation grants No. OTKA-T34980/T29803/-T22929/M28413/OM-MU-708.

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