Determination of Absolute Neutrino Masses from Bursts of *Z* Bosons in Cosmic Rays

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Ultrahigh energy neutrinos (UHEν) scatter on relic neutrinos (Rν) producing Z bosons, which can decay hadronically producing protons (Z burst). We compare the predicted proton spectrum with the observed ultrahigh energy cosmic ray (UHECR) spectrum and determine the mass of the heaviest Rν via a maximum likelihood analysis. Our prediction depends on the origin of the powerlike part of the UHECR spectrum: $m_\nu = 2.75^{+1.28}_{-0.97}$ eV for Galactic halo and $0.26^{+0.20}_{-0.14}$ eV for extragalactic origin. The necessary UHEν flux should be detected in the near future.

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I. Introduction.—The interaction of protons (p) with photons (γ) of the cosmic microwave background radiation (CMBR) predicts a sharp drop in the cosmic ray flux above the Greisen-Zatsepin-Kuzmin (GZK) cutoff around 4×10^{19} eV [1]. The available data show no such drop. About 20 events above 10^{20} eV were observed by experiments such as AGASA [2], Fly's Eye [3], Haverah Park [4], Yakutsk [5], and HiRes [6]. The attenuation length of protons above the GZK cutoff is $\approx$50 Mpc; but no obvious astrophysical source candidate is known within this distance. No conventional explanation for the observed ultrahigh energy cosmic ray (UHECR) spectrum is known [7].

Already in the early 1980's there were discussions that the UHEν spectrum could have absorption dips at energies around $E^{\rm res}_{\nu_i} = M_Z^2/(2m_{\nu_i}) = 4.2 \times 10^{21}$ $(1\ {\rm eV}/m_{\nu_i})$ eV due to resonant annihilation with the relic neutrinos (Rνs) predicted by the hot big bang cosmology, into Z bosons of mass M_Z [8,9]. Recently it was realized that the same annihilation mechanism gives a possible solution to the GZK problem [10]. It was argued that the UHECRs above the GZK cutoff are mainly from Z bursts taking place within the GZK zone of $\approx$50 Mpc.

This hypothesis was discussed in several papers [11–16]. In Ref. [11], particle spectra were determined numerically for case studies which supported the Z-burst scenario. The required UHEν fluxes for different spectral indices were calculated in Ref. [12], too. The effect of possible lepton asymmetries was studied in Ref. [13]. In Ref. [15], the analysis of the Z-burst mechanism was advocated as one of the few possibilities for an absolute ν mass determination and its potential compared to others such as, e.g., the β decay end point spectrum and the ν-less $\beta\beta$ decay.

There is now rather convincing evidence that νs have nonzero masses (cf. [17]). This evidence comes from ν oscillation measurements with typical mass splittings $\sqrt{\delta m^2} \sim 10^{-5}$–0.4 eV. Neutrinos in this mass range are important cosmologically since they represent a nonnegligible contribution to dark matter (DM) which imposes upper limits on ν masses [18]. Hydrodynamic simulations with massive νs and including recent observational measurements and cosmological constraints give [19] $\sum_i m_{\nu_i} \lesssim 2.4(\Omega_M/0.17-1)$ eV, if the matter content of the universe Ω_M is assumed to be between 0.2 and 0.5, as favored by recent measurements (cf. [17]).

II. Z-burst spectrum and UHECR data.—Our comparison of the Z-burst scenario with the observed UHECR spectrum is done in four steps. First we determine the probability of Z production as a function of the distance from Earth. In the second step we exploit collider experiments to derive the energy distribution of the produced protons in the lab system. The third ingredient is the propagation of the protons, i.e., the determination of their energy loss 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 spectrum and the extraction of the mass of the Rν and the necessary UHEν flux.

For a given neutrino type i the probability of Z bursts at some distance r is proportional to the number density $n_{\nu_i}(r)$ of the Rνs and to the flux $F_{\nu_i}(E_{\nu_i}, r)$ of the UHEνs at energy $E_{\nu_i} \approx E^{\rm res}_{\nu_i}$. The density distribution of Rνs as hot DM follows the total mass distribution; however, it is expected to be less clustered. This is the reason why we, similarly to Ref. [14] but in distinction to practically all previous authors [10–12], do not follow the assumption of having a relative overdensity of $f_\nu = 10^2$–10^4 in our neighborhood. For distances below 100 Mpc we varied the shape of the $n_{\nu_i}(r)$ distribution between the homogeneous case and that of $m_{\rm tot}(r)$, the total mass distribution obtained from peculiar velocity measurements [20]. Our results are rather insensitive to these variations. Their effect is included in our error bars. For scales larger than 100 Mpc the Rν density is given by the big bang cosmology, $n_{\nu_i} = 56(1 + z)^3$ cm^{-3}. In our analysis we go up to distances of redshift $z = 2$ (cf. [21]). We include uncertainties of the expansion rate (see e.g., Section 2 of [17]). The UHEν flux is assumed to have the form $F_{\nu_i}(E_{\nu_i}, r) = F_{\nu_i}(E_{\nu_i}, 0)(1 + z)^\alpha$, where α characterizes the source evolution (see also [9,11]). Independently of the production mechanism, ν oscillations result in a uniform F_{ν_i} mixture for the different types i.

The Z-burst scenario is based on Z decays. At LEP and SLC millions of Z bosons were produced and their decay analyzed with extreme high accuracy. 69.89% of the Z decays are hadronic and the $p + \bar{p}$ multiplicity is $\langle N_p \rangle = 1.04 \pm 0.04$ in the hadronic channel [17]. The neutron multiplicity, which we included in our analysis, is $\approx$4% smaller than the proton's [22]. We combined existing published and some improved unpublished data on the momentum distribution $\mathcal{P}(x = p_{\rm proton}/p_{\rm beam})$ of protons in Z decays [23]. Because of the large statistics, the uncertainties related to Z decay are negligible.

In the CM system of the Z production the angular distribution of the hadrons is determined by the spin 1/2 of the primary quarks and thus proportional to $1 + w^2 = 1 + \cos^2\theta$ [here θ is the angle between the incoming neutrinos and the outgoing hadrons (cf. [24])]. The energy distribution $\mathcal{Q}(E_p)$ of the produced protons with energy E_p is finally obtained after a Lorentz transformation from the CM system to the lab system,

$$\mathcal{Q}(E_p) = \frac{2}{E_\nu} \sum_{+,-} \frac{3}{8} \int_{-1}^{1} dw (1 + w^2) \frac{1}{1 - w^2} \left| \frac{\pm y - w\sqrt{y^2 - (1 - w^2)(2m_p/M_Z)^2}}{\sqrt{y^2 - (1 - w^2)(2m_p/M_Z)^2}} \right| \times \mathcal{P}\{[-wy \pm \sqrt{y^2 - (1 - w^2)(2m_p/M_Z)^2}]/(1 - w^2)\}, \quad (1)$$

where m_p is the p mass and $y = 2E_p/E_\nu$.

Particles of EG origin and energies above $\approx 4 \times 10^{19}$ eV lose a large fraction of their energies [1]. This can be described by the function $P(r, E_p, E)$, the probability that a proton created at a distance r with energy E_p arrives at Earth above the threshold energy E [25]. It has been calculated for a wide range of parameters in Ref. [26]. Note that the energy attenuation length of γs is longer than that of protons roughly by a factor of 10 at superhigh energies such as 10^{21} eV. The detailed study of the boosted Z-decay (data from Ref. [23]) results in γs of energy below 10^{19} $(1\ {\rm eV}/m_{\nu_i})$ eV, where their attenuation length is much smaller, for strong enough radio background. Thus, their contribution to the UHECR spectrum is far less relevant than that of the protons.

The Z-burst contribution to the UHECR spectrum, for degenerate ν masses ($m_\nu \approx m_{\nu_i}$), is given by

$$j(E, m_\nu) = I F_Z^{-1} \cdot \int_0^\infty dE_p \int_0^{R_0} dr \int_0^\infty d\epsilon \quad (2)$$

$$\sum_i F_{\nu_i}(E_{\nu_i}, r)\sigma(\epsilon) n_{\nu_i}(r) \mathcal{Q}(E_p)[-\partial P(r, E_p, E)/\partial E],$$

where $I \approx 8 \times 10^{16}$ m^2 s sr is the total exposure (estimated from the highest energy events and the corresponding fluxes), R_0 is the distance at $z = 2$, and $\sigma(\epsilon)$ is the Z production cross section at CM energy $\epsilon = (2_\nu m_{\nu_i})^{1/2}$. The normalization factor F_Z is proportional to the sum of the ν fluxes at CM energy M_Z.

We compare the spectrum (2) with the observed one and give the value of m_ν based on a maximum likelihood analysis. In the Z-burst scenario a small Rν mass needs large $E_\nu^{\rm res}$ in order to produce a Z. Large $E_\nu^{\rm res}$ results in a large Lorentz boost, thus large E_p. In this way the detected E determines the mass of the Rν.

Our analysis includes the published and the unpublished (from the www pages of the experiments on 17/03/01) UHECR data of [2–4,6]. Because of normalization difficulties we did not use the Yakutsk [5] results.

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: $\log(E_{\rm min}/{\rm eV}) = 18.5$. Our results are insensitive to the definition of the upper end (the flux is extremely small there) for which we choose $\log(E_{\rm max}/{\rm eV}) = 26$. As usual, we divided each logarithmic unit into ten bins. The integrated flux gives the total number of events in a bin. 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. For the degenerate case, the predicted number of events in a bin is given by

$$N(i) = \int_{E_i}^{E_{i+1}} dE[AE^{-\beta} + F_Z j(E, m_\nu)], \quad (3)$$

where E_i is the lower bound of the ith energy bin. The first term is the usual power law, which describes the data well for smaller energies [2]. For this term we will study two possibilities. In the first case we assume that the power part is produced in our galaxy. Thus no GZK effect should be included for it ("halo"). In the second—in some sense more realistic—case we assume 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 will be modified and falls off around 4×10^{19} eV (see later Fig. 1). The second term of the flux in Eq. (3) corresponds to the spectrum of the Z bursts, Eq. (2). A and F_Z are normalization factors.

The expectation value for the number of events in a bin is given by Eq. (3) and it is Poisson distributed. To determine the most probable value for m_ν we used the maximum likelihood method and minimized [27] the $\chi^2(\beta, A, F_Z, m_\nu)$ for Poisson distributed data [17],

$$\chi^2 = \sum_{i=18.5}^{26.0} 2[N(i) - N_o(i) + N_o(i)\ln(N_o(i)/N(i))], \tag{4}$$

where $N_o(i)$ is the total number of observed events in the ith bin. In our fitting procedure we have four parameters: β, A, F_Z, and m_ν. The minimum of the $\chi^2(\beta, A, F_Z, m_\nu)$ function is $\chi^2_{\min}$ at $m_{\nu\min}$, the most probable value for the mass. The 1σ confidence interval for m_ν is given by $\chi^2(\beta', A', F_Z', m_\nu) = \chi^2_{\min} + 1$. β', A', F_Z' are defined by minimizing $\chi^2(\beta, A, F_Z, m_\nu)$ in β, A, and F_Z at fixed m_ν.

Our best fits to the observed data can be seen in Fig. 1, for evolution parameter $\alpha = 3$. The neutrino mass is $2.75^{+1.28(3.15)}_{-0.97(1.89)}$ eV for the "halo"—and $0.26^{+0.20(0.50)}_{-0.14(0.22)}$ eV for the "EG" case, respectively. The first numbers are the 1σ, the numbers in the brackets are the 2σ errors. This gives an absolute lower bound on the mass of the heaviest ν of 0.06 eV at the 95% C.L. Note, that the surprisingly small uncertainties are based on the above χ^2 analysis and dominantly statistical ones. The fits are rather good; for 21 nonvanishing bins and 4 fitted parameters they can be as low as $\chi^2 = 18.6$. We determined m_ν for a wide range of cosmological source evolution ($\alpha = 0$–3) and Hubble parameter $[H_0 = (71 \pm 7) \times {}^{1.15}_{0.95}\text{km/sec/Mpc}]$ and observed only a moderate dependence on them. The results remain within the above error bars. For these mass scales the atmospheric or solar ν experiments suggest practically degenerate ν masses. This has no influence on our ν mass determination, but is taken into account in our flux determination.

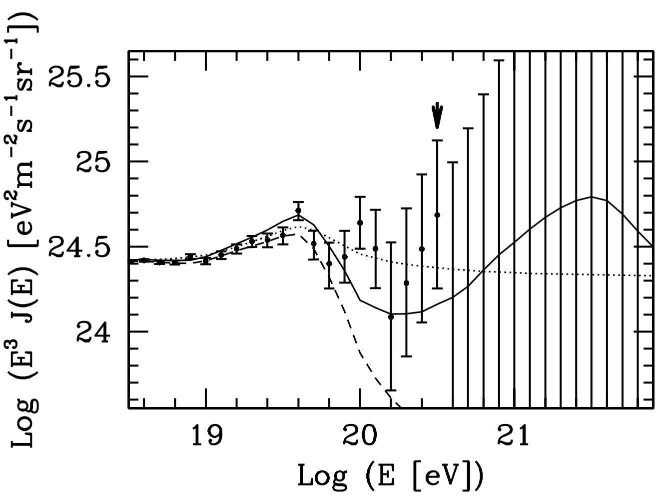

FIG. 1. The available UHECR data with their error bars and the best fits from Z bursts. Note that there are no events above 3×10^{20} eV (shown by an arrow). The dotted line shows the best fit for the "halo" case. The bump around 4×10^{19} eV is due to the Z-burst protons, whereas the almost horizontal contribution is the first, power-law-like term of Eq. (3). The solid line shows the "extragalactic" case. The first bump at 4×10^{19} eV represents protons produced at high energies and accumulated just above the GZK cutoff due to their energy losses. The bump at 3×10^{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 falloff for this term around 4×10^{19} eV can be observed. The attenuation of the Z-burst component appears to be weaker on account of the narrowness of the injected proton spectrum and the fact that the observed post-GZK protons are produced within the GZK zone.

We performed a Monte Carlo analysis studying higher statistics. In the near future, Auger [28] will provide a 10 times higher statistics, which reduces the error bars in the neutrino mass to ≈ one-third of their present values.

One of the most attractive patterns for ν 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 ν oscillation for the heaviest mass [17], 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 ν oscillation solution, the other two—muon and tau—by the atmospheric ν 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 1σ region in the m_1–m_2 plane is shown in Fig. 2 for the "EG" case. Since this two-mass scenario has fewer constraints the allowed region for the masses is larger than in the one-mass scenario.

III. Necessary UHEν flux.—The necessary UHEν flux at E_ν^{res} can be obtained via Eqs. (2) and (3) from our fits. We have summarized them in Fig. 3, together with some existing upper limits and projected sensitivities of present, near future, and future observational projects. The

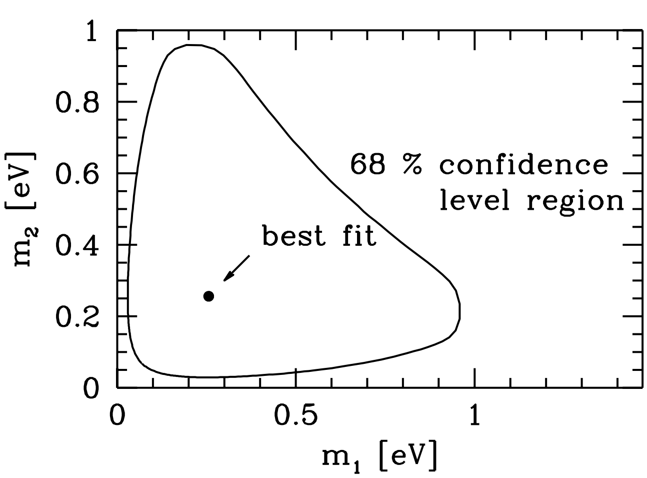

FIG. 2. The best fit and the 1σ (68% C.L.) region in a scenario with two nondegenerate ν masses.

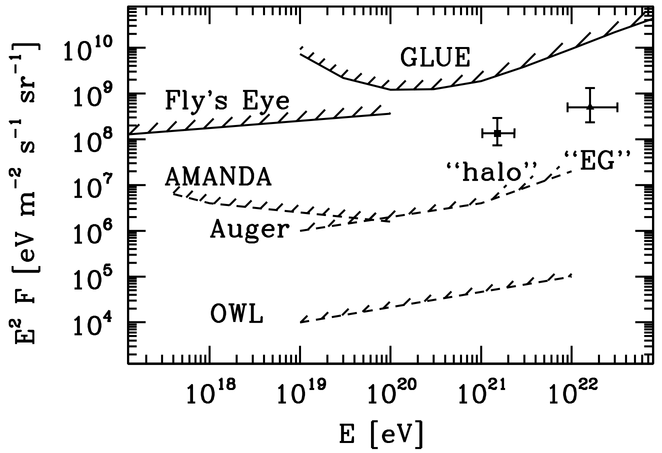

FIG. 3. Neutrino fluxes, $F = \frac{1}{3}\sum_{i=1}^{3}(F_{\nu_i} + F_{\bar{\nu}_i})$, required by the Z-burst hypothesis for the "halo" and the "extragalactic" case, for evolution parameter $\alpha = 3$. The horizontal errors indicate the 1σ uncertainty of the mass determination and the vertical errors include also the uncertainty of the Hubble expansion rate. The dependence on α is just of the order of the thickness of the lines. Also shown are upper limits from Fly's Eye [29] and the Goldstone lunar ultrahigh energy neutrino experiment GLUE [30], as well as projected sensitivities of AMANDA [31], Auger [11,32], and OWL [11,33].

necessary ν flux appears to be well below present upper limits and is within the expected sensitivity of AMANDA, Auger, and OWL. Clearly, our fluxes are higher than the ones found in Ref. [11] based on local overdensities f_ν. However, since we also have a background the normalization of the Z-burst component is different and correspondingly our fluxes are somewhat less than a factor of f_ν higher. An important constraint for all top-down scenarios [7] is the EGRET observation of a diffuse γ background [34]. As a cross check, we calculated the total energy in γs from Z bursts. We assumed that all energy ends up between 30 MeV and 100 GeV. Our γ flux is somewhat smaller than that of EGRET.

IV. Conclusions.—We compared the predicted spectrum of the Z-burst hypothesis with the observed UHECR spectrum. We should emphasize that only a realistic overdensity of Rνs was used. We determined the mass of the heaviest Rν: $m_\nu = 2.75^{+1.28}_{-0.97}$ 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% C.L., is compatible with a hierarchical ν mass scenario with the largest mass suggested by the atmospheric ν oscillation. The necessary UHEν flux should be detected in the near future.

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