PHYSICAL REVIEW D, VOLUME 60, 017302

Implications for the cosmic ray spectrum of a negative electron neutrino (mass)^2

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(Received 10 September 1998; revised manuscript received 5 March 1999; published 26 May 1999)

The features and problems of a speculative model based on the electron neutrino being a tachyon are discussed. The model is consistent with five properties of the cosmic ray spectrum, and it predicts a flux of neutrons in a narrow energy region centered on $4.5 \pm 2.2 \times 10^{15}$ eV. [S0556-2821(99)00315-X]

PACS number(s): 14.60.St, 14.60.Pq, 95.85.Ry, 96.40.De

I. INTRODUCTION

Following a suggestion by Kostelecký [1], we posit the electron neutrino to be a tachyon with $|m_\nu| \equiv \sqrt{-m^2} \approx 0.5\ \mathrm{eV}/c^2$, and consider the consequences for the cosmic ray (CR) spectrum. The hypothesis, while it is highly speculative, is consistent with other neutrino observations, and it predicts the existence of a CR neutron flux in a narrow range of energies centered on $4.5 \pm 2.2 \times 10^{15}$ eV.

Tachyons, first postulated in 1962, by Bilaniuk, Deshpande, and Sudarshan [2], are taken seriously by few physicists, because of the paradoxes they create, and because nearly [3] all experiments specifically [4] searching for tachyons have turned up negative [5,6]. Whatever one's view of tachyons, their existence is clearly an experimental question. Weakly interacting tachyons of low mass would have probably escaped detection, or else not be recognized as such. In fact, Chodos, Hauser and Kostelecký suggested in 1985 that neutrinos are tachyons [7].

Chodos *et al.* [8,9] noted that one could test this hypothesis using a strange tachyon property, i.e., that particle decays producing tachyons which are energetically forbidden in one reference frame are allowed in another. Thus, consider the ''decay'' $p \rightarrow n + e^+ + \nu_e$. For the decay to conserve energy in the proton rest frame, we need $E_\nu < 0$. Now, tachyons, unlike other particles, have $E < p$ so they can change the sign of E when boosted to a sufficient velocity. Thus, the tachyon energy in the proton rest frame E_ν has the opposite sign from its energy in the lab $E_{lab} = \gamma(E_\nu + \beta p_\nu \cos\theta)$ when β exceeds $-E_\nu/p_\nu \cos\theta < 1$.

The threshold lab energy for protons to decay is found by making E_ν the least negative it can be in the c.m. frame, i.e., $-E_\nu = m_n + m_e - m_p \equiv \Delta$, and taking $\cos\theta = 1$. Therefore, at threshold $\beta_{th} = -E_\nu/p_\nu \approx 1 + \frac{1}{2} m_\nu^2/E_\nu^2$, and hence $\gamma_{th} = (1-\beta_{th}^2)^{-1/2} = \Delta |m_\nu|^{-1}$, so that

$$E_{th} = \gamma_{th} m_p = \frac{m_p \Delta}{|m_{\nu e}|} = \frac{1.7 \times 10^{15}}{|m_{\nu e}|}\ \mathrm{eV}. \tag{1}$$

For nuclei of mass number A, m_p is the mass of the parent nucleus, and $\Delta = m(A, Z \pm 1) + m_e - m(A,Z)$. The idea of ''stable'' particles decaying is less paradoxical if one reinterprets the emitted ν with $E_\nu > 0$ in the lab frame to be an absorbed $\overline{\nu}$ with $E_{\overline{\nu}} < 0$ from a background sea in the proton rest frame — the so-called ''reinterpretation principle'' [2,7]. This antineutrino background sea defines an absolute reference frame, presumably coincident with that defined by the cosmic background radiation (CBR).

In order to test the prediction of Chodos *et al.* as applied to the CR spectrum, we need to calculate the mean free path for protons and other stable cosmic ray nuclei to decay as a function of their energy. Although we can easily deduce the threshold for such decays from kinematic arguments, finding the decay rates requires a knowledge of tachyon dynamics. One might assume that the phase space involving negative energy tachyons could be treated in a similar manner as for positive energy particles. Under this assumption the decay rate for $p \rightarrow n + e^+ + \nu$ could be estimated by integrating that tiny region of phase space in the c.m. for which E_ν changes sign between the c.m. and lab frames, and also assuming that the usual weak interaction coupling constant applies to the process. However, the validity of such an approach is questionable. Given the reinterpretation principle, the rates for the processes $p \rightarrow n + e^+ + \nu$ and $\overline{\nu_{bs}} + p \rightarrow n + e^+$ must be identical for any given proton energy. But the reaction rate of the latter reaction depends on both known antineutrino cross sections as well as the unknown density of antineutrinos in the background sea ($\overline{\nu_{bs}}$), and hence we have no way to estimate reliably the $p \rightarrow n + e^+ + \nu$ decay rate. This being the case, we simply make an assumption that holds promise for explaining the knee of the CR spectrum: at all proton energies significantly above threshold that the rate for proton decay greatly exceeds that for conventional neutron decay.

II. MODELLING THE COSMIC RAY SPECTRUM

The idea that tachyonic neutrinos might explain the knee of the CR spectrum was first raised by Kostelecký, though he regarded the existence of the knee by itself as insufficient evidence for the hypothesis in view of other explanations of the knee [1]. Moreover, Kostelecký neither modelled the CR spectrum, as is done here, nor mentioned the signature neutron spike. The inputs to the model are assumptions for (1) $|m_{\nu_e}|$ values, (2) the energy spectrum and composition of CR's at their source, and (3) the spatial distribution of sources.

For the spatial distribution, we take an admixture of ''near'' and ''far'' sources. Near sources are assumed to create CR's having path distances to Earth from 10^4 to 2×10^6 ly, and far sources are assumed to have path distances from 2×10^6 to 10^8 ly. For the source spectrum we use an $E^{-2.67}$ power law that fits the spectrum up to 10^{15} eV. Es-

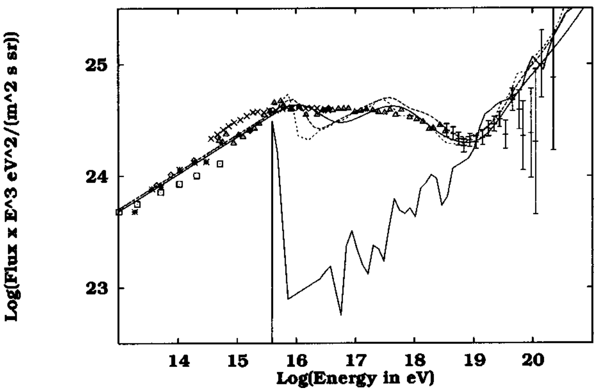

FIG. 1. Upper solid curve shows the prediction of the model for the CR flux, dn/dE, ($\times E^3$) assuming a tachyon mass $|m| = 0.5$ eV/c^2, with convolution, using an energy resolution of $\Delta \log E = \pm 0.4$. The two dashed curves show fits with $|m_\nu| = 0.25$ eV/c^2: short dashed curves assume $\Delta \log E = 0$, and the long dashed curve uses $\Delta \log E = \pm 0.2$. The lower solid curve shows the predicted neutron spectrum component using $|m| = 0.5$ eV/c^2 and $\Delta \log E = 0$. All curves assume 13% near sources with mass compositions noted in the text. Points are the data from JAYCEE (diamonds), AGASA (with error bars), Aoyama-Hirosaki (squares), Tibet (crosses), Akeno 1 km^2 array (diamonds), and Proton Satellite (asterisks).

sentially, we assume that the source spectrum is $E^{-2.67}$ for all E, and that changes in the observed spectrum are due to particles in a given energy bin being shifted to lower energies as a result of beta decay. Since the composition of CR's above the knee is not well known, we try various compositions to fit the data.

The Monte Carlo method was used to obtain Figs. 1–3. Protons and nuclei were generated at various distances from Earth, and the fate of all particles in a given energy bin was considered to be the same, as their progress toward Earth was followed. For protons leaving sources above the threshold energy for decay, there is a chain of decays $p \rightarrow n \rightarrow p \rightarrow n \rightarrow p \cdots$ which stops when the nucleon either reaches Earth or else has its energy reduced below threshold. As long as E is above threshold, the nucleon spends most of its time en route from the source as a rectilinearly propagating neutron, because the mean free path for neutrons before they decay is much greater than that for protons except quite close to E_{th}. A similar decay chain occurs in the case of $A > 1$ CR nuclei. After each decay the daughter nucleus has less energy in the lab frame than the parent. Calculating the energy loss of the nucleon in a conventional beta decay such as $n \rightarrow p + e^- + \overline{\nu_e}$ is straightforward. In the c.m. frame the proton has very little energy following the decay, and hence in the lab frame the nucleon loses a constant fraction $f \approx (1 - m_p/m_n)$ of its energy. For the energetically forbidden decay, such as $p \rightarrow n + e^+ + \nu_e$, the situation is more complex. Here for proton lab energies much above threshold the neutrino needs to have highly negative energies in the c.m. so that its energy in the lab frame be positive, and hence the daughter nucleus energy can no longer be ignored in the c.m. frame. The calculation can be done as a sequence of two two-body decays: e.g., $p \rightarrow m(n,e^+) + \nu_e$ followed by $m(n,e^+) \rightarrow n + e^+$, where in the first decay we choose only those events having $E_{lab} > 0$.

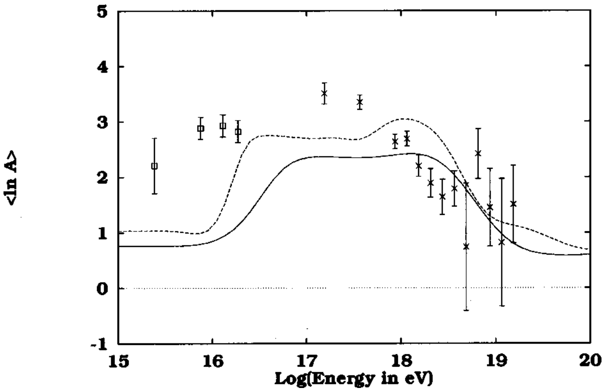

FIG. 2. Prediction of the model for the CR composition ($\langle \ln A \rangle$) as a function of particle energy. Solid and dashed curves makes the same assumptions for $|m_\nu|$, composition, and the percentage of ''far'' CR sources as the solid and dashed curves shown in Fig. 1. Data points with squares are BASJE (1994), and crosses are Fly's Eye (1993).

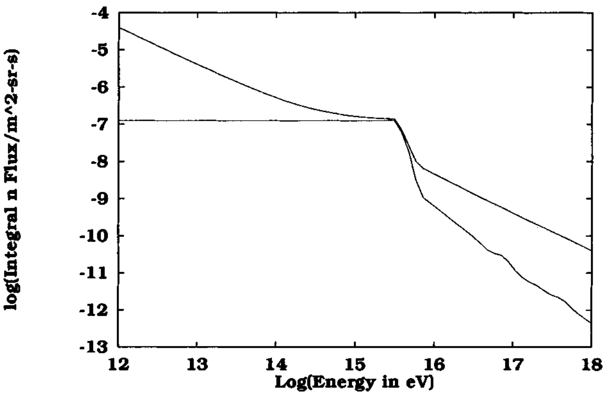

FIG. 3. Lower curve shows the prediction of the model for the log of the CR flux of neutrons integrated above an energy E, assuming $|m_\nu| = 0.5$ eV/c^2, 13% near sources, with no convolution to account for finite energy resolution. The upper curve shows the log of the integrated neutron flux atop a hypothetical $1/E$ background one tenth its amplitude at the position of the spike.

We show in Fig. 1 the log of the all particle flux ($\times E^3$) — both data and calculation. A reasonably good fit to the spectrum is obtained for $|m_\nu| = 0.5$ eV/c^2 (solid curve), assuming that 13% of sources are ''near,'' with elemental abundances: 70% A=1, 10% A=4, 10% A=5 to 19, 5% A=20 to 40, and 5% A=41 to 90. The solid curve convolutes the Monte Carlo results with an energy resolution $\Delta \log E = \pm 0.4$ (FWHM). The goodness of fit worsens if the resolution is $\Delta \log E = \pm 0.2$ (long dashes) or zero (short dashes). In these two latter cases, the fits use $|m_\nu| = 0.25$ eV/c^2, and elemental abundances: 65% A=1, 10% A=4, 5% A=5 to 19, 5% A=20 to 40, and 15% A=41 to 90.

No decent fits exist for $|m| \geqslant 0.75$ eV/c^2. All three fits would also dramatically worsen if there were no near sources – since the curves would then drop sharply at $E \approx 10^{19}$ eV.

Thus, the flux beyond this energy appears in the model to come primarily from the 13% of sources that are ''near.'' A convenient way to represent changes in the composition of the CR's is to plot $\langle \ln A \rangle$ versus energy — see Fig. 2. The model results are in rough agreement with the data in its essential features: a rise of $\langle \ln A \rangle$ from the knee of the spectrum to a maximum near 10^{17} to 10^{18} eV and a subsequent decline to a near zero value, i.e., almost pure protons, at 10^{19} eV. Given the difficulty in measuring the composition of CR's above the knee, such rough agreement is not unreasonable.

Exactly what is needed in the model to reproduce the specific features seen in the data?

The knee at $E \approx 4 \times 10^{15}$ eV requires $|m_\nu| \approx 0.5$ eV/c^2, so that threshold energy for CR protons to decay occurs at this energy, and the proton component drops precipitously — jagged curve in Fig. 1.

The E^{-3} power law between $E = 10^{16}$ and 10^{18} eV (near horizontal slope in Fig. 1) is reproduced only with the choice of composition noted previously, and a large enough energy resolution to smooth out the bumps from different element thresholds.

The position of the dip at $E \approx 10^{19}$ eV also depends on the $|m_\nu|$ value. It occurs because at this energy the threshold for the heaviest elements to decay is reached, and the spectrum becomes depleted.

The rise for $E > 10^{19}$ eV, occurs because as E increases, an increasing fraction of A$=$1 particles from the near sources can reach us, given their lengthened lifetime and mfp. This rise needs 13% of sources to be ''near,'' which is how the model ''explains'' the apparent lack of GZK cutoff [10,11].

Composition vs energy (Fig. 2). The composition is heavy before the dip at $E \approx 10^{19}$ because only the heaviest elements are left in the spectrum at this E, since their thresholds have not yet been reached. However, at the highest energies the CR's are found to be very light, because by $E \approx 10^{19}$ eV the thresholds for all $A > 1$ nuclei have been reached, while this E is far enough above E_{th} for A$=$1 that this component is coming back.

The source spectrum was chosen as $E^{-2.67}$ to match the observed spectrum below the knee. Equivalently, any other power law $E^{-2.67+\alpha}$ could have been used if the effect of energy loss processes not included here were simply to steepen the source power law by α. [Of course, the dominant (A$=$1) spectral component should show very little energy loss due to other processes if the nucleons are neutrons during most of their time en route.]

III. POTENTIAL PROBLEMS WITH MODEL

While the model may be consistent with some features of the CR spectrum, that is a far cry from being evidence for tachyonic neutrinos. Let us consider a few of the problems with the model.

Conventional explanations exist for some of the regularities we have noted, and plausible mechanisms exist to account for the production of the component of the spectrum believed to be galactic in origin. However, few conventional explanations predict numerical values for the position of the knee and ankle, and many of the models have both ad hoc elements and free parameters. Moreover, explaining some of the spectral features represents a very severe test of all conventional models – particularly the *abruptness* of the change in slope at the knee and ankle [12].

A source composition independent of energy is highly unrealistic. But by making this assumption we are merely limiting the number of free parameters.

Other models can account for the absence of a GZK cutoff. Various suggestions have been made to explain why CR's with energies above the conjectured GZK cutoff ($E \approx 4 \times 10^{19}$ eV) apparently fail to be significantly degraded in energy by interaction with the CBR [13,14]. Nevertheless, as long as no specific distant sources have been identified, it would seem that the least exotic hypothesis is that CR sources with $E > 4 \times 10^{19}$ eV simply are closer than a few dozen Mpc (as our model requires), *even if no specific sources have so far been identified.*

No mechanisms are known that have a single power law spanning over ten decades. Of course, there are no known sources in the conventional theory of CR's at the highest energies either, though topological defects have been suggested as one possibility [15]. But they have not been proposed to account for the lower energy region, which are believed to originate from supernova shocks. One exotic possibility for sources has been proposed by Kuz'min and Tkachev: the decay of supermassive long-lived particles produced in the early universe [16]. One advantage of this possibility from our point of view is that such sources could be a considerable fraction of cold dark matter, and hence could be prominent in the Milky Way galactic halo, and therefore relatively nearby. Yet, they would also be relatively isotropic, as seems to be the case for the limited number of events so far seen at the highest energies.

IV. POSSIBLE CONFIRMING TESTS

The seven tritium beta decay experiments used by the Particle Data Group [17] all report $m_{\nu e}^2 < 0$. Two of these experiments report $m_{\nu e}^2 < 0$ by over four standard deviations (4σ), but they are also 4σ apart. Regrettably, the value we have used here $|m_{\nu e}| \approx 0.5$ eV/c^2 is too small to be consistent with either of these experiments. Moreover, the tritium results have been explained in terms of either experimental anomalies [18,19], final state interactions, or new physics [21] — though some have attributed them to tachyonic neutrinos [20,22]. If the electron neutrino really were a tachyon, could future tritium beta decay experiments test for values of $m_{\nu e}^2 \approx 0.25$ eV^2/c^4? The current systematic and statistical errors on m^2 are over an order of magnitude larger, so probably not without new types of instruments.

If neutrinos really were tachyons, why should one put any more faith in the mass obtained from a fit to the CR spectrum than the much larger values found in tritium experiments? One answer is that the only statistically significant negative values found in tritium experiments are inconsistent, and have been attributed to other causes. Secondly, if any of the masses from tritium experiments represented real tachyons, then the knee of the CR spectrum would have to occur one or two decades lower in energy than is observed, because the threshold energy for proton decay varies inversely with $|m_{\nu e}|$. Alternatively, if $|m_{\nu e}|$ found from the CR spectrum fit is correct that only means that the values reported in the tritium experiments arise from causes other than tachyons.

Are there other places one might look for confirmation of the tachyonic neutrino hypothesis? Neutrino oscillation experiments, being sensitive to Δm^2 cannot reveal whether individual neutrino flavors have $m^2 < 0$, and mass limits from the 1987A or future supernovae would seem to lack the needed sensitivity. There is, however, one unambiguous test of the tachyonic neutrino hypothesis involving a CR neutron flux — see Fig. 1.

The signature of the model is a spike of neutrons just above the threshold energy for proton beta decay at $E = 4.5 \pm 2.2 \times 10^{15}$ eV. The uncertainty in the spike's position corresponds to the range: $0.25 < |m| < 0.75$ eV/c^2. The pile up of neutrons just above E_{th} is a consequence of the fractional energy loss of the nucleon becoming very small as E_{th} is approached from above. Given distances to CR sources, virtually all neutrons below E_{th} decay to protons long before reaching Earth. As can be seen in Fig. 3, the neutron spike might even be seen in plots of the integrated flux if the background were small enough.

Based on air shower measurements, it may be impossible to distinguish individual n's from p's in the region of the knee of the spectrum, But, there is one clear difference: unlike protons or nuclei, multiple neutrons should point back to specific sources. Moreover, given the neutron lifetime, the mfp before decay at an energy of 10^{16} eV is only about 200 ly — much too close for many sources in any conventional model. As Fig. 1 shows, neutrons should also be seen as a large component of the flux at energies above 10^{19} eV. However, if neutrons were seen at these energies, they could well be the result of sources closer than 0.2 Mly, and they would, therefore, have little value in confirming the hypothesis of tachyonic neutrinos.

ACKNOWLEDGMENTS

The author thanks Peter Becker, Jochen Bonn, Alan Chodos, Robert Ellsworth, Alan Kostelecký, Dietrich Muller, Jonathan Ormes, Len Ozernoy, Jakub Rembielinski, Todor Stanev and John Wilkerson for helpful suggestions.

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