Is there a 4.5 PeV neutron line in the cosmic ray spectrum?

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(Received 8 April 1999; published 7 September 1999)

Recently we presented a model to fit the cosmic ray spectrum using the hypothesis that the electron neutrino is a tachyon. The model predicted the existence of a neutron flux in the cosmic rays in a narrow region centered on $E = 4.5 \pm 2.2$ PeV. The published literature on Cygnus X-3 reveals just such a 6σ spike of neutral particles centered on $E = 4.5$ PeV. A second prediction of the model concerning integrated neutron fluxes at several energies also is consistent with published data. A specific further test of the model is proposed. [S0556-2821(99)01019-X]

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

I. INTRODUCTION

Recently we presented a model to fit the high energy cosmic ray spectrum using the hypothesis that the electron neutrino is a tachyon [1]. A good fit to the spectrum was obtained using $|m_\nu| \equiv \sqrt{-m^2} = 0.5 \pm 0.25$ eV/c^2. The signature prediction of the model is the existence of a neutron flux "spike" in the cosmic rays centered on $E = 4.5 \pm 2.2$ PeV, and having a width $\Delta \log E = 0.1$ [full width at half maximum (FWHM)]. Although the existence of neutral cosmic rays from point sources remains a highly controversial subject, we report here that an examination of the published literature on cosmic rays from Cygnus X-3 reveals just such a hitherto unreported neutral particle spike centered on $E = 4.5$ PeV with a level of statistical significance of 6σ. An additional prediction of the model that the integrated flux of neutrons above 0.5 EeV should be 0.048% that above 2 PeV is also consistent with results from two out of three experiments.

Although few physicists have taken tachyons seriously since they were first proposed in 1962 [2], their existence is clearly an experimental question. In 1985 Chodos, Hauser, and Kostelecký [3] suggested that neutrinos were tachyons—an idea that is consistent with experiments used to determine the neutrino mass. Chodos and co-workers [4,5] also suggested a remarkable empirical test of the tachyonic neutrino hypothesis, namely that stable particles should decay when they travel with sufficiently high energies. Consider, for example, the energetically forbidden decay $p \to n + e^+ + \nu_e$. In order to conserve energy in the c.m. frame the neutrino would need to have $E < 0$. But tachyons with $m^2 < 0$ have $E < p$, and therefore the sign of their energy in the laboratory frame $E_{lab} = \gamma(E + \beta p \cos\theta)$ will be positive for a proton velocity $\beta > \beta_{th} \equiv -E/p \cos\theta$. With the aid of a little kinematics it can easily be shown that the threshold energy for proton decay is $E_{th} \approx 1.7|m_\nu|^{-1}$ PeV, with $|m_\nu|$ in eV/c^2.

Thus, if neutrinos are tachyons, energetically forbidden decays become allowed when the parent particle has sufficient energy—in seeming contradiction with the principle of relativity that whether or not a process occurs should not depend on the observer's reference frame. That contradiction is only an apparent one, however, because what appears to the laboratory observer as a proton decay emitting a neutrino appears to the c.m. observer as a proton absorbing an antineutrino from a background sea.

II. COSMIC RAYS

Since cosmic rays bombard the Earth with energies far in excess of what can be achieved in present day accelerators, it is natural to ask whether any evidence for a process such as proton decay exists there at very high energies. One striking feature of the cosmic ray spectrum is the "knee" or change in power law that occurs at $E \approx 4$ PeV. Various two-source mechanisms have been suggested to account for this spectral feature, but some researchers have identified it as arising from a single type of source [6]. In 1992 Kostelecký [7] suggested that for a tachyonic neutrino mass $|m_\nu| \approx 0.3$ eV, the proton decay threshold energy occurs at the knee of the cosmic ray spectrum, and could explain its existence. The idea is that cosmic ray nucleons on their way to Earth would lose energy through a chain of decays $p \to n \to p \to n \to \cdots$, which would deplete the spectrum at energies above E_{th}. However, Kostelecký regarded the existence of the knee by itself as insufficient evidence for the tachyonic neutrino hypothesis in view of other more conventional explanations of the knee of the cosmic ray spectrum. He also did not attempt to model the spectrum, nor mention the signature neutron spike.

Recently this author has developed a tachyonic neutrino model that fits a number of features of the cosmic ray spectrum in addition to the knee [1]. These include the existence and position of the "ankle" (another change in power law at $E \approx 6$ EeV), the specific changes in power law at the knee and ankle, the changes in composition of cosmic rays with energy, and the ability of cosmic rays to reach us above the conjectured Greisen-Zatsepin-Kuz'min (GZK) "cutoff" [8,9]. Although the fit to the cosmic ray spectrum was a good one, the model is highly speculative, because it is at variance with conventional wisdom about cosmic rays and it arbitrarily assumed that the decay rate for protons (for $E > E_{th}$) was far greater than that for neutrons.

Nevertheless, the model did make the striking prediction of a cosmic ray neutron flux in a narrow range of energies just above E_{th}—a neutron "spike." The pile up of neutrons in a narrow interval just above E_{th} is a consequence of the fractional energy loss of the nucleon in proton decay becoming progressively smaller, the closer the proton energy gets to E_{th}. The position of the predicted cosmic ray neutron spike depends on the value assumed for $|m_\nu|$. From the fit to

TABLE I. Experiments reporting integrated fluxes (or upper limits) in units of $\times 10^{-14}$ particles $cm^{-2} sec^{-1}$ for Cygnus X-3 for PeV energies. Only experiments reporting nonsporadic signals claimed to be at a level of more than 4σ have been listed. The van der Klis and Bonnet-Bidaud ephemeris has been used for finding the phase interval in each case.

Ref.	Years	E in PeV	Flux	Stat. sig.	Phase
[11]	76–79	>2	7.4 ± 3.2	4.4σ	0.1–0.3
[20]	78–81	>1	<3		
[22]	79–82	>3	1.5 ± 0.3	5σ	0.225–0.25
[21]	86–88	>1	2.7 ± 0.5	4.7σ	0.25–0.30
[18]	89	>1	<23		
[19]	90–95	>1.175	<0.1		

the cosmic ray spectrum we found $|m_\nu| = 0.5 \pm 0.25 \, eV/c^2$, and hence we predicted a neutron spike at $E = 4.5 \pm 2.2 \, PeV$. In fact the model predicted that most nucleons should be neutrons for $E > E_{th}$, because it was assumed that as nucleons lose energy in the $p \to n \to p \to \cdots$ decay chain, the lifetime and hence the decay mean free path for neutrons is far greater than for protons, and so nucleons above E_{th} would spend nearly all of their time en route as neutrons [10]. But, the model also predicts that for energies above the spike the neutron component does not become an appreciable fraction of the total cosmic ray flux until around 1 EeV. While neutrons might reach Earth at EeV energies in conventional cosmic ray models, it would be difficult to understand any sizable neutron component at energies as low as $E = 4.5 \, PeV$, where the neutron mean free path before decay would be only about 100 light-years. In the present model, however, $A = 1$ cosmic rays can travel very many neutron decay lengths and still arrive as neutrons because many steps of the $p \to n \to p \to \cdots$ decay chain occur for nucleons having energies above E_{th}.

III. CYGNUS X-3 DATA

One way to look for a neutron flux would be to find a cosmic ray signal that points back to a specific source, since neutrons are unaffected by galactic magnetic fields. Starting in 1983 a number of cosmic ray groups did, in fact, report seeing signals in the PeV range from Hercules X-1 and Cygnus X-3. At the time these signals were believed to be either gamma rays or some hitherto unknown long-lived neutral particle, since neutrons, as already noted, should not live long enough to reach Earth (except in the present model). Some of the experiments coupled detection of extensive air showers with detection of underground muons [11,12]. The observed high muon intensity was found to be consistent with hadrons but not with showers induced by gamma rays [12,13]. It was widely believed that the mass of the neutral particle was $m \approx 1 \, GeV/c^2$ [14]. Thus, all the observed or conjectured properties of these particles were consistent with neutrons: neutral strongly interacting particles with $m \approx 1 \, GeV/c^2$.

Following a period of excitement in the 1980s, many researchers began to look critically at some of the observations of ultra–high-energy cosmic rays from point sources. This

skepticism was based in part on the inconsistencies between results reported in different experiments. As Chardin and Gerbier have noted [15], a number of papers used data selection procedures that made direct comparisons difficult, e.g., using different phase intervals to make cuts, variously reporting the total flux or only the flux in a particular phase bin, and reporting only ''muon-poor'' events. Also, some papers appeared to inflate the statistical significance of their results.

But, the most serious challenge to the idea of neutral particles in the PeV range from Cygnus X-3 and other point sources came from a trio of high sensitivity experiments [16–18] that reported seeing no signals from point sources claimed earlier. In the most sensitive experiment of the three, the upper limit on the flux of neutral particles from Cygnus X-3 above 1.175 PeV was far below the fluxes reported by those experiments claiming signals earlier [19]. There seems to be only two possibilities: either *all* the earlier experiments claiming signals were in error, or Cygnus X-3 and other reported sources all had turned off about the time improved instrumentation became available. Table I offers some support for the latter possibility, because (a) the phases of the signals are in rough agreement in three experiments, and (b) the integrated flux above a PeV does appear to systematically decrease over time taking all experiments together. (Among those claiming signals only those claiming more than 4σ have been listed, and among those citing upper limits only those giving upper limits on the flux above a PeV have been listed.) The suggestion that signals from Cygnus X-3 have fallen with time was first raised by Rana *et al.* based on x-ray and gamma ray data in four different wavelength regions [23]. In what follows, we make the ''optimistic'' assumption that earlier experiments were seeing real signals, and we consider to what extent those reports of signals from Cygnus X-3 support the prediction of a 4.5 PeV neutron spike.

In the 1980s there were eight cosmic ray groups that cited fluxes in the PeV range of signals pointing back to Cygnus X-3 (some which were inconsistent as mentioned earlier). In nearly all cases limited statistics required reporting the flux integrated over energy in only one or at most two energy intervals.

One group (Lloyd-Evans *et al.* [22]), however, had good enough statistics to report fluxes in eight energy bins spanning the location of the predicted 4.5 PeV neutron spike, and it had an energy acceptance threshold near $E_0 = 1 \, PeV$,

TABLE II. Observed and expected event counts reported by Lloyd-Evans *et al.* in differential energy bins for the phase interval 0.225–0.250. The last column has been added by the author. The ''expected'' counts for each energy interval are based on the average over all phases.

E (in PeV)	Observed	Expected	Excess$\pm \sqrt{\text{expected}}$
1–3	16	13.9	2.1 ± 3.7
3–5	34	16.4	17.6 ± 4.0
5–11	17	6.2	10.8 ± 2.5
11–18	4	2.4	1.6 ± 1.6
18–36	3	4.3	-1.3 ± 2.1
36–72	6	3.4	2.6 ± 1.8
72–140	2	0.8	1.2 ± 0.9
>140	0	0.6	-0.6 ± 0.8

which could give one energy bin before the spike itself. The signal seen by Lloyd-Evans *et al.* from Cygnus X-3 did not appear until the data is selected on the basis of orbital phase determined from the x-ray binary's 4.79 h orbital period, and the time of signal arrival. Lloyd-Evans *et al.* found that if they looked at the number of counts in 40 phase bins, one of these bins showed a sizable excess (73 counts when the average was 39). The information in Table II is taken from Lloyd-Evans *et al.* [22], with the last column added by this author. Figure 1 displays the data in that last column. We would expect a flat distribution on the basis of chance, assuming that the signal were just a statistical fluctuation. In fact, averaged over all phases, the distribution must be flat and zero height, regardless of whether the signal is real or not. Note that a spike appears centered on the value predicted by the tachyonic neutrino model, and that all the remaining bins have a flux consistent with zero. The Gaussian curve drawn with arbitrary height in the figure shows what would be predicted by the model given a neutron spike of width $\Delta \log E = 0.1$ (FWHM) and a 50% energy resolution ($\Delta \log E = \pm 0.176$). According to Lloyd-Evans, the actual
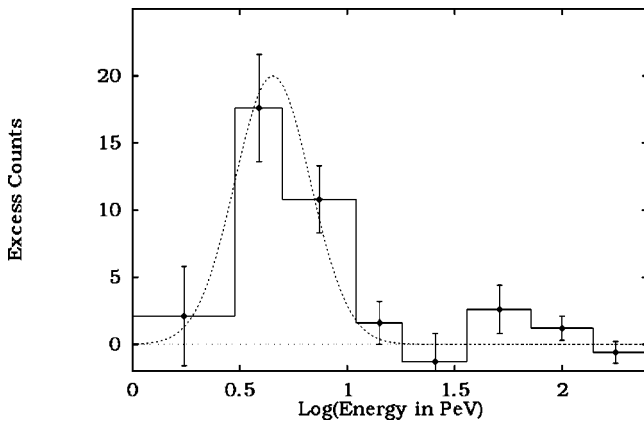

FIG. 1. Data points from the last column of Table II plotted at the middle of each interval in $\log E$ in PeV. The Gaussian curve centered on 4.5 PeV is what one would expect to find in Lloyd-Evans data, given a neutron spike of width $\Delta \log E = 0.1$ (FWHM), and a 50% energy resolution ($\Delta \log E = \pm 0.176$).

resolution was probably around 50%, and very likely less than 100% [24]. We estimate the statistical significance of this spike occurring by chance by dividing the excess number of events in the two bins straddling 5 PeV by the square root of the expected number of events in those two bins: $28.4 / \sqrt{22.6} = 6.0\sigma$. It is interesting that in their article, Lloyd-Evans *et al.* displayed only the integrated flux I ($>E$) versus energy, and hence failed to mention the spike. Instead, they simply noted that the integrated spectrum appeared to steepen right after 10 PeV.

How can we be sure that the spike seen in the data of Lloyd-Evans *et al.* is not an artifact of the data analysis or a statistical fluctuation? Six standard deviations may seem interesting, but the original peak in their phase plot was far less impressive, particularly allowing for a ''trials factor'' of 40, since such a peak might have been seen in any one of the 40 phase bins. Suppose that in fact the original peak in the phase plot were a statistical fluctuation, how could one then get a 6σ peak in the flux versus energy distribution for events in a specific phase bin? Clearly, such a peak would require some correlation between energy and phase. This could in principle occur, because observed cosmic ray energy is correlated with declination angle, and hence with time of day. However, all cosmic rays in a given phase bin arrive at one of five, i.e., 24/4.79, times throughout the day, and those arrival times slowly advance from day to day, since the Cygnus X-3 period is not exactly divisible into 24 hours. Thus, over the years of data-taking each phase bin would sample times of the day with an almost uniform distribution, making it difficult to see how a phase-energy correlation could occur.

(It could be that at their source the phase and energy of cosmic rays are correlated, but in that case we would be dealing with a real source, not a statistical fluctuation, as hypothesized above.)

Ideally, one would want to combine the data of Lloyd-Evans *et al.* with that of other experiments in the PeV region to see if the spike either is destroyed or enhanced. Several problems arise with the other existing data, in which a signal is claimed from Cygnus X-3: one experiment used only ''muon-poor'' events [25], two experiments reported only the integral flux above some energy (no energy bin defined) [26,27], two reported the flux in an energy bin three times the width used by Lloyd-Evans [11,28], and none was contemporaneous with Lloyd-Evans, thereby severely diminishing their utility.

Aside from the spike, one other prediction of the tachyonic neutrino model is that neutrons should also be seen as a significant and rising fraction of the cosmic ray flux above around 1.0 EeV. In fact, two cosmic ray groups have reported seeing neutral particles from Cygnus X-3 having energies above 0.5 EeV with fluxes of 1.8 ± 0.7 [29], and 2.0 ± 0.6 [30], while a third group reporting merely an upper limit to the flux <0.4 [31]—all in units of 10^{-17} particles $\text{cm}^{-2}\text{s}^{-1}$.

These measured fluxes above 0.5 EeV can be compared directly with the neutron flux predictions from the tachyonic neutrino model [1]. As noted previously, the ratio of the integral flux of neutrons above 0.5 EeV to that above 2 PeV is predicted to be $R = 4.8 \times 10^{-4}$. The predicted neutron flux

for $E>0.5$ EeV is then R times the measured flux reported by Lloyd-Evans *et al.* for $E>2$ PeV, or $R\times7.4\pm3.2\times10^{-14}=3.5\pm1.5\times10^{-17}$ particles cm^{-2}s^{-1}, which is in quite good agreement with the two groups that measured a flux, rather than an upper limit. Although subsequent data accummulation by these two groups failed to show a signal from Cygnus X-3 [32], that only adds additional support to the hypothesis that the source faded over time.

If it is true that Cygnus X-3 and other point sources were active in the early 1980s and subsequently have turned off, is there any way to check whether there really is a 4.5 PeV neutron spike without waiting for specific sources to come back on? Without knowing where the sources are, the model can make no prediction of the anisotropy or the the angular distribution of sources of high energy cosmic rays. However, recall that the model predicts that *all* the cosmic rays include a 4.5 PeV neutron spike, not just those pointing back to the handful of possible sources looked at so far. Thus, if one selects events in a narrow energy band centered on 4.5 PeV, one could look at their arrival directions on the two dimensional map of the sky, and see if there is a noticeable clustering of points, which would indicate neutral particles coming from specific sources. Moreover, if those sources were episodic, one should observe a nonuniform distribution in arrival times for events for a given source.

Consider a specific example. The integrated flux in the 4.5 PeV spike is 0.1 neutrons per m^2 sr s, which would give around 3×10^6 counts over 5 years for an array of area 250 000 m^2. If the array had an energy resolution of 100%, it would also record a background count rate roughly four times as great in the energy bin centered on 4.5 PeV. Suppose the angular resolution were $\Delta\theta=0.01$ rad, which would allow up to $4/\Delta\theta^2=4\times10^4$ solid angle bins to be defined. Each bin would then have on the average 400 background counts. Further suppose that the cosmic rays reaching Earth came from N point sources, then those solid angle bins pointing back to sources would have an average signal to background ratio: $10^4/N$. Identification of sources should then be possible, unless N were larger than the number of solid angle bins, and no subset of sources were appreciably brighter than others.

IV. SUMMARY

In summary, a highly speculative tachyonic neutrino model [1], which fits the cosmic ray spectrum well, predicts a spike of neutrons at an energy where, given the neutron lifetime and distance to likely sources, very few should appear. A search through the literature for sources of neutral cosmic rays has identified a particular experiment with a favorable energy acceptance threshold, good enough statistics, and enough energy bins spanning the region of the neutron spike to test the prediction. The data do show a 6σ spike located right at the predicted energy, which was not identified in the original work. The failure of other subsequent more sensitive experiments to see a signal from Cygnus X-3 would seem to require that this source has since turned off—a possibility given some support by both time trends of data from different experiments, and data within the same experiments. The characteristics of the neutral particles from Cygnus X-3 seem to be consistent with neutrons rather than gamma rays, based on muon data from various experiments. For the EeV region, where the model also predicts neutrons (though not a spike), two out of three experiments show a positive signal from Cygnus X-3, and they report a flux whose magnitude (relative to the flux in the spike) is well predicted by the model. The hypothesis that the electron neutrino is a tachyon would seem to be supported, and it can be further tested without waiting for specific point sources to come back on.

ACKNOWLEDGMENTS

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