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Possible Test for the Suggestion that Air Showers with $E > 10^{20}$ eV are due to Strongly Interacting Neutrinos

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Abstract

The suggestion is made that air showers with energies beyond the Greisen- Zatsepin-Kuz'min spectral cut-off may have primary vertices some 6 km lower in height than those of proton initiated showers with energies below the GZK cut-off. This estimate is based on the assumption that post-GZK showers are due to neutrinos having acquired strong interactions from generation-changing dual gluon exchange as recently proposed.

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Air showers at the highest known energies of around 10^{20} eV [1]-[6] have long been a puzzle to cosmic ray physicists in that protons at such energies are thought not to be able to survive a long journey through the 2.7 K cosmic microwave background [7, 8], while no nearby sources are known which seem capable of producing such energetic particles. Recently, following earlier work [9]-[13], a suggestion was made that these showers may be due to neutrinos having acquired strong interactions at these energies [14]. Neutrinos, being stable and electrically neutral, are not subject to the Greisen-Zatsepin-Kuz'min spectral cut-off and can in principle reach the earth from distant sources even at these energies. That they could possibly have acquired at these energies a strong interaction and sufficient cross section for them to initiate air showers is suggested by a favourite hypothesis of particle physicists that fermion generations are a consequence of a broken gauge symmetry, which hypothesis is in turn supported by a recent proposal that this symmetry may be related to dual colour [15]. If this is true, then the phenomenon is linked to flavour-changing neutral current hadron decays, and estimates for their branching ratios have been derived which can serve as tests for the hypothesis [14].

So far, however, two things are lacking in this recent proposal: (i) an estimate of the neutrino-air nucleus cross section showing that it is indeed sufficient for producing air showers as observed, and (ii) a direct test for the hypothesis with air shower data. The purpose of this note is to suggest possible amendments to these deficiencies.

Strong interactions, though necessary, are in themselves not sufficient to guarantee a large cross section.[1] If the range of the interaction is short, then the cross section is limited by unitarity to a size characteristic to that range, irrespective of the strength of the interaction. Thus, if we were to picture the target in a collision as a disc, then, however strong the interaction, it cannot make the disc appear blacker than black. Now, since the strong interaction of the neutrino in the above proposal is supposedly due to the exchange of generation-changing gauge bosons which have masses in the hundred TeV range, then the question arises whether the neutrino will ever have enough (hadronic-sized) cross section with air nuclei to initiate air showers in our

[1] We are indebted to J.D. Bjorken for a reminder of this fact during a talk by one of us at the Cracow Summer School in June, 1997, which started us on the following train of thought.

atmosphere. In other words, will a nucleon in the air nucleus appear to the neutrino as just a number of small black dots representing the partons inside it rather than as a black disc of hadronic size?

In a general framework of generation-changing gauge bosons mediating the assumed new strong interactions, the answer would seem to point to the former alternative. Since the mass of the new gauge bosons is bounded below by the experimental limits on flavour-changing neutral current decays to be in the range of 10 to several 100 TeV [16], the range of the interactions would seem to be only of the order of 10^{-5} fermi. The nucleon will then appear to the neutrino as a collection of very small dots and give cross sections only of the order of 10^{-12} barns, certainly not enough to initiate air showers.

On the other hand, if we were to accept the suggestion in [15] that generation is in fact (spontaneously broken) dual colour, a possibility we have already considered [14], then the situation would seem to be entirely different. The dual gluons which are supposed to mediate the new strong interaction between the neutrino and the partons inside the nucleon do not represent a different degree of freedom to colour. Indeed, in the picture suggested in [15], the dual gluon and the gluon can "metamorphose" into each other. Outside the hadron, the gluon does not propagate, and interactions mediated by exchanges of dual gluons will be short-ranged. Once inside the hadron, however, where the gluon does propagate, the suggestion in [15] was that the range of the interaction will be governed by the zero gluon mass and become infinite. The neutrino will thus interact with the nucleon coherently and see the nucleon as a disc, not as a collection of little black dots. In other words, one expects the neutrino-nucleon cross section to be hadronic in size, and not so very small as in the previous scenario.

Indeed, arguing along these intuitive lines, one might even attempt a crude estimate of the neutrino-air nucleus cross section as follows. Suppose that the air nucleus does appear to the neutrino as a black disc of radius r_A but that the neutrino, with yet unknown internal structure, appears still as a point. Then the neutrino-nucleus cross section is simply given as πr_A^2. Compare this now to the proton-nucleus cross section. The proton and the nucleus will appear to each other as (almost) black discs, the proton with radius r_p, say. Assuming that the proton and the nucleus will both break up as soon as they touch, one would suggest that the proton-nucleus cross section would be given as $\pi(r_A+r_p)^2$. Assuming further that $r_A = r_p A^{1/3}$, A being the atomic number of the air nucleus, which we take on the average to be say 15, we obtain r_A to be about 2.47 r_p. From this one can naively conclude that the neutrino-nucleus cross section is about half the proton-nucleus cross section. Although this way of estimating cross sections is admittedly crude, it is seen to give sensible values for proton–nucleus and proton–nucleon cross sections, with reasonable proton and nuclear radii, and should thus, we think, be good enough also for guessing the high energy neutrino-nucleus cross section for the purpose we wish to use it.

Suppose this is true. We conclude first that neutrinos at these energies will have enough cross section to initiate air showers, and secondly, since the cross section is smaller than for protons, the neutrino will be somewhat more penetrating and initiate air showers at lower altitudes on the average. The second fact, we believe, may be used as a criterion to distinguish neutrino showers statistically from proton showers and hence test the original suggestion that the highest energy showers are initiated by neutrinos rather than protons.

It is not difficult to make our statement above more quantitative. Air density varies with height h in cm above sea-level roughly as:

$$\rho(h) = 1.2\ (\exp -h/h_0) \times 10^{-3}\mathrm{gm/cm}^3, \tag{1}$$

with the attenuation length:

$$h_0 = 7.6 \times 10^5\mathrm{cm}. \tag{2}$$

Suppose the flux of a particle has initial value f_{inc}. Let θ be the angle to the zenith at the point the shower axis hits the earth's surface and x the distance from this point measured aloong the shower axis. Then the flux, after penetrating to the point (x, θ), will be attenuated to the value:

$$f(x,\theta) = f_{inc} \exp\left\{K(\sigma)\int_{\infty}^{x} dx' \rho(h(x',\theta))\right\}, \tag{3}$$

where the height h expressed in terms of x and θ is:

$$h = \sqrt{R^2 + 2xRcos\theta + x^2} - R, \tag{4}$$

with R being the radius of the earth. The attenuation constant K is:

$$K(\sigma) = (N/A)\sigma, \tag{5}$$

where N is the Avogadro number, A the atomic number of the air nucleus, and σ the incident particle-nucleus cross section. For protons, K^{-1} is about 60 gm/cm^2 at these high energies, and if we were right in our estimate above, K would be about one half of this value for neutrinos.

The probability for effecting a collision and producing an air shower at x and θ is then:

$$F(x, \theta) = K(\sigma)\rho(h(x, \theta))f(x, \theta). \tag{6}$$

This, being a product of two exponentials, one decreasing and the other increasing with height, has a maximun at some x which will then be the most likely place where an air shower will be initiated. In Figure 1, we show the distribution function F of the "primary vertex" for respectively proton- and neutrino-initiated showers as a function of x at $\theta = 0$, i.e. vertically down. One sees that the maxima for protons and neutrinos differ by around 6 km in height, with proton showers occuring at around 21 km and neutrino showers at around 15 km.

We conclude therefore that if, as suggested, showers below the GZK cut-off are mostly proton-initiated while those above the GZK cut-off are neutrino-initiated, then the primary vertices of those below GZK should cluster around 21 km in height while those above GZK should cluster at around 15 km.[2] The maxima in both distributions being quite sharp, as seen in Figure 1, the clusters should be well-separated from one another.

The calculation can be repeated for all incident angles θ giving very similar distributions, although the maximum and also the width of the maximum will depend on θ. In Figure 2, we plot the positions of the distribution maxima for varying θ, for both the proton and the neutrino. One sees that the two curves are well-separated with the neutrino curve lying much lower than the proton curve. If we take each event and plot the position of its primary vertex on Figure 2, the prediction is that pre-GZK events representing proton showers will cluster around the top curve while post-GZK events representing neutrino showers will cluster around the bottom curve, with a clear separation between them.

[2]This assumes that detection efficiency has been folded in.

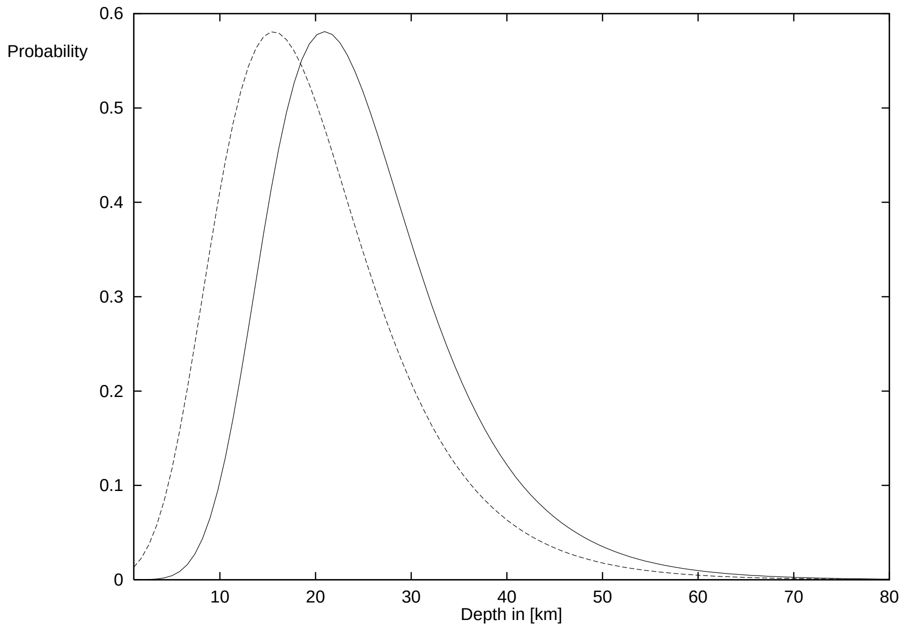

Figure 1: Probability distributon (arbitrary units) of primary vertices for proton-initiated (full curve) and neutrino-initiated (dotted curve) air showers.

We recognize that the primary vertex is in most experiments difficult or perhaps even impossible to determine accurately. But in a detector like the Fly's Eye [4], the development profile of the shower is measured, and by examining the profile function closely near the beginning one may get a reasonable idea of where the primary vertex is located. As an exercise, we take the development profile of the highest energy shower known at 3.2×10^{20} eV detected by Fly's Eye and look for the point where fluorescence was first detected, which was at a depth of around 200 gm/cm^2. This corresponds to a vertical height of around 12 km or to $x = 19.5$ km for the observed $\theta = 43^0.9$. If we boldly call this the primary vertex and plot it on Figure 2, we obtain the

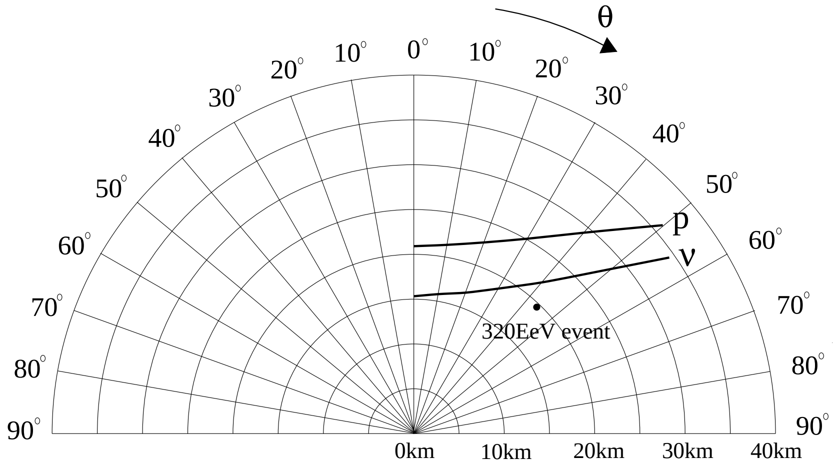

Figure 2: The positions of the distribution maxima for varying θ

point shown. From Figure 1 we see that the probability of a proton shower having its primary vertex at or lower than 12 km is only about 5 percent, which means that, other things being equal and taking this information at its face value, it would seem that this event is much more likely to be from a neutrino as suggested in [14] than from a proton. We realize, of course, that we have been extremely naive to identify the primary vertex as the point when light first shows in the Fly's Eye detector, which identification should have been made only by the experimenters themselves after a careful analysis of the shower development profile, the detection efficiency etc. For all we know, the shower might have started much higher up without showing any light. However, as far as the method is concerned, it would seem that, given the development profiles of two showers with primary vertices differing by as much as 6 km in height, there should be no difficulty in distinguishing them. It appears to us therefore that with the data collected by Fly's Eye, it may already be possible to decide whether the suggestion is feasible. In any case, for the Auger project [6] which has also the Fly's Eye's facility, only better, it seems that with some effort, it ought to be a relatively simple matter.

If such a separation is indeed seen in experiment, then it would be a rather good test of the hypothesis that pre- and post-GZK showers are initiated by different particles with different cross sections. In view of the absence of any other stable particles known, with hadronic yet somewhat smaller cross section than the proton, it would seem then that there is a fair chance of the latter being initiated by neutrinos. The converse, however, would be harder to conclude if no clear difference in height is seen since the neutrino cross section used in the analysis above has been so crudely estimated. Nevertheless, it seems to us an attempt worth making since the prize is so attractive.

The crude picture outlined in the beginning for high energy neutrino interactions suggests in fact also some differences in the development of showers due respectively to neutrinos and to protons. The neutrino in this picture being elementary and the proton composite, it seems that the development profile of neutrino-initiated showers would differ from that that of proton-initiated showers in much the same way that showers initiated by nuclei differ from those initiated by protons. However, the average number of partons in the proton being probably small compared with the number of nucleons in a (say iron) nucleus, the difference would be less marked and we are not sure it would be noticeable. We think that the difference in height of the "primary vertex" as described above would be a more hopeful means for differentiating the two primaries.

Looking further, suppose we are convinced by further analysis based on the above method or otherwise that air showers beyond the GZK cut-off are indeed due to neutrinos. Then by turning the argument around, we might imagine using the Auger project [6] as an apparatus for measuring the high energy neutrino cross section. For example, if we draw the contours of the type shown in Figure 2, one for each value of σ, then by plotting each event observed above the GZK cut-off in the figure and seeing on which contour it lies, we obtain for it some value of σ. If we next plot the number of post-GZK events against σ, we shall be able to read off directly the neutrino-nucleus cross section from the position of the peak of the distribution.

Going further still, we might even imagine using the Auger project as a spectrometer for studying the mass spectrum of generation-changing gauge and Higgs bosons. In the incoming neutrino beam, there will be presumably also anti-neutrinos, and if generation-changing bosons do exist, then an anti-neutrino on hitting an electron present in the atmosphere can form one of these bosons provided that the collision occurs at the right energy. The highest shower known at present has $E = 3.2 \times 10^{20}$ eV corresponding in a collision with an electron to a C.M. energy of around 18 TeV, which is not far from the estimates for the masses of the lowest generation-changing Higgs bosons obtained from the dual scheme [15, 17]. Should the spectrum for cosmic ray neutrinos extend further up, and at the moment we do not know any reason why it should not, then the Auger project should be able to sweep the mass region from 10 TeV upwards and see generation-changing bosons occuring as resonance peaks in a manner similar to that in ordinary spectroscopy experiments.

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