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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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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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Extremely high energy cosmic rays, cosmic neutrinos, flavour-changing neutral currents, duality.

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.

The problem of estimating the high energy neutrino-nucleus cross section is not one that can be solved straightforwardly just given the premises of a new strong interaction for neutrinos mediated by generation-changing gauge bosons. It is a highly nonperturbative problem on two counts. First, if the coupling is strong - as indeed it will be if one accepts the interpretation of generation as dual colour as proposed in [15] where the Dirac quantization condition gives the new coupling as $\tilde{\alpha}_3 \sim \alpha_3^{-1} \sim 10$ - then a perturbative expansion in powers of the coupling would be impossible. And, secondly, which is even more difficult and applies even if the coupling is not so large, the cross section of interest to us involves a hadron which is itself a consequence of the nonperturbative effect of confinement in QCD. To obtain an estimate, therefore, no simple perturbative argument will suffice but further insight will be needed. One recalls that even in ordinary QCD, where the interaction is much better understood than the proposed generation-changing

interaction, perturbative arguments apply only to hard processes which have cross sections many orders of magnitudes smaller than the total. Indeed, no method we know starting from the QCD action, not even those with some input grafted on from soft hadron physics such as the Regge theory, nor yet from the Regge theory itself, is able to make a statement about the actual size of high energy hadron cross sections, let alone reproducing their values. On the other hand, a simple geometric picture is often found capable of yielding the right orders of magnitude for hadronic total cross sections. Take for example, pp collision. If we picture the proton as a black disc say of radius $r_p \sim 1$ fermi, we obtain the pp cross section simply as $4\pi r_p^2$ or roughly 120 mb, which is not at all a bad estimate compared with experiment. We propose therefore to adopt this picture here for the crude estimate of high energy neutrino cross section that we need. This does not mean, of course, a departure from the framework suggested in [15] and [14] but a development of it by using the experience gained from soft hadron physics so as to estimate hadron cross sections which are otherwise beyond our present capability.

To proceed then along these lines, we note first the important point that strong interactions though necessary are in themselves insufficient 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 however strong the interaction may be. Thus, if we were to picture the target in a collision as a disc with a radius of the order of the interaction range, then, however strong the interaction, it cannot make the disc appear blacker than black or the cross section large than the size of the disc. Now, 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, so its range will necessarily be very short. Then the question arises whether the neutrino will ever have enough (hadronic-sized) cross section with air nuclei to initiate air showers in our atmosphere.

Imagine then a neutrino approaching an air nucleus at these ultra high energies. The nucleus is, of course, made up of nucleons and the nucleons of quarks, and it is with the quarks which carry generation or dual colour that the neutrino interacts by the mechanism described above. If this interaction

¹We are indebted to J. 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.

is indeed short-ranged, will the air nucleus not appear to the neutrino just as a number of small black dots representing the partons inside it rather than as a black disc of hadronic size? If the former were the case, then since the mass of the new gauge bosons are 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 nucleus will then appear to the neutrino as a collection of very small dots and give cross sections only of the order of 10^{-11} barns, certainly not enough to initiate air showers. Indeed, this would seem to be the likely scenario in a general framework where the new generation-changing interaction is mediated by gauge bosons representing an entirely new degree of freedom.

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.

Proceeding along these intuitive lines, one might then 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.

Notice that the estimate of a ratio of about a half for the cross section of neutrino-nucleus to that of proton-nucleus is likely to be rather stable. The main uncertainty in estimating cross sections by the geometric picture is what one should assume for the hadron radius, but this uncertainty largely cancels in taking the ratio of cross sections. The estimate is thus expected also not to depend much on the energy, provided of course that the energy is already high enough for the new strong generating-changing interactions to be operative. In the geometric picture as usually interpreted, the energy-dependence of cross sections translates into an energy-dependence of the hadronic radii. A change in energy gives then just a change in scale of r_A and r_p above and does not change the predicted ratio between neutrino-nucleus and proton-nucleus cross sections. Nor is the ratio expected to depend much on the dual gauge boson coupling and mass. Once the coupling strength is large enough, which it would be by the previous estimate, the nucleus will look black to the neutrino and little changes in the coupling strength will make no difference. And once the neutrino enters into hadronic matter, it will interact with the latter coherently irrespective of the dual gauge boson mass.

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 [17]:

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

with the attenuation length:

$$h_0 = 7.6 \times 10^5 \text{ cm.} \quad (2)$$

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 along the shower axis. Then the flux, after penetrating to the point (x, θ) , will be attenuated to the value:

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

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

$$h = \sqrt{R^2 + 2xR\cos\theta + x^2} - R, \quad (4)$$

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

$$K(\sigma) = (N/A)\sigma, \quad (5)$$

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:

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

This, being a product of two exponentials, one decreasing and the other increasing with height, has a maximum 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 occurring 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

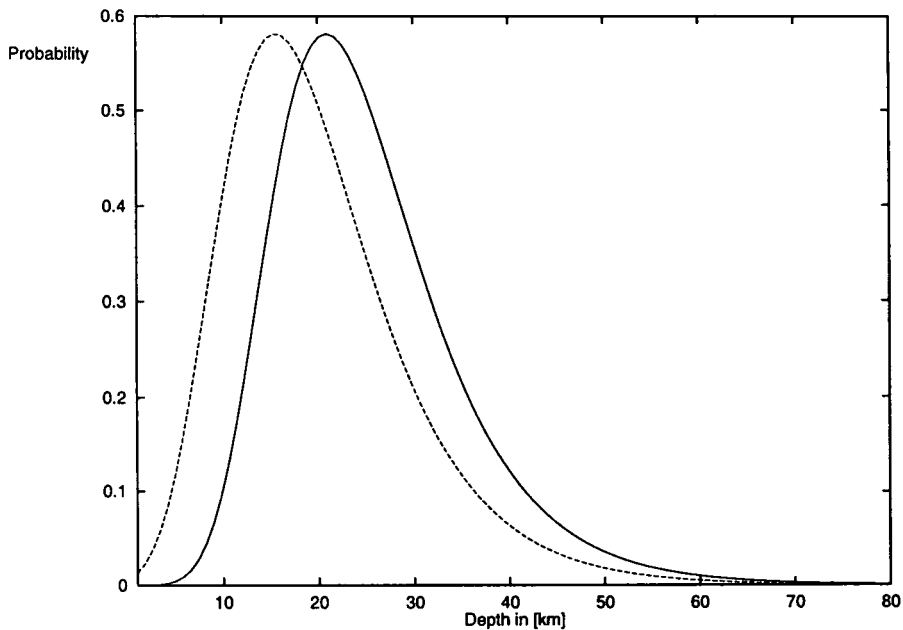


Figure 1: Probability distributon (arbitrary units) of primary vertices for proton-initiated (full curve) and neutrino-initiated (dotted curve) air showers.

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 represent-

²This assumes that detection efficiency has been folded in.

ing 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.

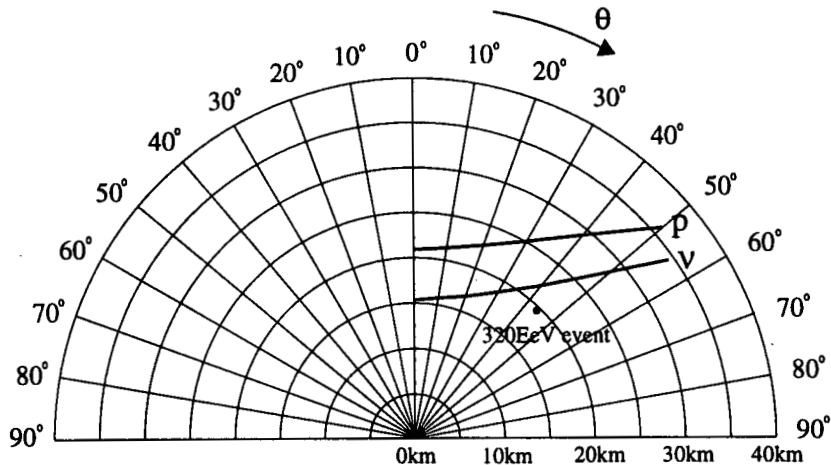


Figure 2: The positions of the distribution maxima for varying θ

Both the Figures 1 and 2 are based on the traditional value for the attenuation length $K^{-1}(\sigma)$ of protons in air of around 60 gm/cm^2 . This corresponds to a proton-air nucleus cross section of around 420 mb , or by our above reckoning to a proton-proton cross section of around 140 mb , which is roughly what would be obtained by extrapolating the measured pp cross section to 10^{19} eV [17]. At the highest energies measured, the pp cross section still seems to be increasing by about 15 percent for every decade increase in beam energy so that one should expect a similar increase in height of the primary vertex as depicted in the above figures. However, what is important is that the ratio between the neutrino and proton cross sections with the air nucleus, as already noted, is expected to be constant with energy so that a clear separation should remain between the two types of showers initiated respectively by neutrinos and protons, thus allowing them to be distinguished by experiment.

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/cm². This corresponds to a vertical height of around 12 km or to $x = 19.5$ km for the observed $\theta = 43^{\circ}.9$. If we boldly call this the primary vertex and plot it on Figure 2, we obtain the 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 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, 18]. 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 occurring as resonance peaks in a manner similar to that in ordinary spectroscopy experiments.

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