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Post-GZK Air Showers, FCNC, Strongly Interacting Neutrinos and Duality[1]

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Abstract

A review is given on the recently proposed idea that air showers with energy $> 10^{20}$ eV beyond the Greisen-Zatsepin-Kuz'min cut-off may be due to neutrinos having acquired a strong interaction at these energies, as suggested by the Dualized Standard Model. Such a hypothesis is shown to be consistent with the so far known facts. Further, by linking the astrophysical puzzle of post-GZK air showers through electric-magnetic duality to the problem of fermion generations in particle physics, one obtains on the one hand estimates for the rates of some flavour-changing neutral current decays which are accessible to experiments being planned, and on the other direct tests on the hypothesis performable by new air shower detectors such as Auger. The suggestion does not exclude other explanations for post-GZK showers given in the literature. However, we diagree with a recent paper by Burdman, Halzen and Gandhi which sweepingly claimed to have excluded nearly all explanations by new particle physics including ours.

[1]Review talk delivered by Chan Hong-Mo at the International Workshop on Physics Beyond the Standard Model (Oct. 1997) at Valencia, Spain, to appear in the proceedings.

In what follows we shall review briefly an idea recently suggested in [1]. It is a proposed marriage between two long-term puzzles in two rather different fields. The first is the problem in cosmic ray physics of air showers with primary energy higher than 5×10^{19} eV, which theoretically ought not to exist. The other is in particle physics proper, namely the existence of 3 and only 3 generations of fermions, which up to now has had no generally accepted explanation.

Let me begin by outlining first the air shower puzzle. Over the last thirty years, evidence has accumulated for the existence of air showers with primary energies greater than 10^{20} eV [2, 3, 4, 5, 6]. To-date, about 9 such events have been recorded by several detectors using a variety of detection techniques, which makes it rather unlikely for all of them to be due to experimental biases or errors. These are dramatic events. They occur some 12 km up in the atmosphere, and when they hit the earth, they generally cover an area of a few square kilometers in a shower containing as many as 10^{11} charged particles. If we could see them with the naked eye, they would be more spectacular than any fire-work display. And according to Jakov Pfaudler, the energy they carry is not far short of that of one of Boris Becker's serves. It is mainly to investigate further these so-called EHECR's (extremely high energy cosmic rays) that the huge Auger project is being planned, involving large arrays on two sites, one in each hemisphere, totalling in area 6000 km^2 [7].

The reason for this unusual amount of interest, of course, is not because they are spectacular but because they pose an intriguing question the answer to which may reveal to us a new physics horizon. The point is that air showers with such energies ought not in theory to be there at all. Air showers at high energies are thought to be initiated mostly by protons, and protons at such an energy would quickly lose it by interacting with the photons in the 2.7 K microwave background field via, for example, the interaction:

$$p + \gamma_{2.7K} = \Delta + \pi. \tag{1}$$

Indeed, it has been shown by Greisen [8] and by Zatsepin and Kuz'min [9] that the spectrum of protons originating from more than 50 Mpc away should be cut off sharply at around 5×10^{19} eV in traversing the microwave background field. Thus, the observed air showers with energies in excess of 10^{20} eV at experimental energy resolutions of order 20 percent would be a blatant contradiction to theoretical expectations unless their primary protons have an origin within that sort of distances. However, such nearby sources are thought to be unlikely for the following reason. Over such short distances, protons with these extreme energies will be hardly deflected by the magnetic fields either in our galaxy or in the space between. The observed directions of the air showers should thus point directly to their sources, but no candidate sources have been found within a distance of 50 Mpc which are thought capable of producing particles of such an enormous energy.

A possible alternative explanation, among others, for these showers is that they are not initiated by protons at all but by some other particles. Thus a stable zero-charged particle, such as a neutrino, could survive the long journey from whatever its extragalactic origin through the microwave background to arrive on earth with its high energy intact [10, 11, 12]. However, a neutrino with only the known electroweak interactions can readily penetrate our atmosphere. In order to interact with the air at all to produce air showers at the observed frequency, cosmic neutrinos at these energies would need to have a very large flux, which is hardly imaginable. Even if this high flux is indeed available, the air showers induced would have angular and depth distributions which are at variance with those observed. Whereas neutrino initiated showers are expected to be mostly horizontal, in order that the neutrino may pass through sufficient air for it to effect a collision, the observed events (with angular resolution of only $1^o - 2^o$), nearly all have incident angles of less than 40^o from the zenith. Further, air showers initiated by weakly interacting neutrinos would have a flat distribution in the depth of atmosphere penetrated, not bunched at high altitudes as observed. One concludes, therefore, that if neutrinos have only the known electroweak interactions, then the observed air showers with energies greater than 10^{20} eV are very unlikely to be initiated by neutrinos.

On the other hand, if neutrinos have interactions which become strong at ultra-high energies then the objections raised in the paragraph above no longer apply and neutrinos may afford an explanation for the events under consideration. This conjecture has been considered on the basis of possible substructures to quarks and leptons yet unknown to us [13, 14]. What we have suggested [1] is that there is another, perhaps more attractive, theoretical scenario which will naturally give such interactions. This leads then to the other puzzle we mentioned, namely that of fermion generations in particle physics which goes as follows.

Neutrinos, like other leptons and quarks, are known to exist in three generations. This fact has no explanation in the conventional formulation of the standard model but is merely introduced into the theory as a phenomenological requirement, and as such has remained one of the greatest mysteries in particle physics. Now, a favourite suggestion among theoreticians is that generations may in fact represent the quantum numbers of a broken continuous symmetry like $SU(3)$. To bring it into line with other known continuous symmetries, we would then want this new one to be also a gauge symmetry. If so it has to be mediated by a new set of gauge bosons and these, being flavoured but uncharged, would lead in turn to flavour-changing neutral currents (FCNC). Now, such gauge bosons will have to be very heavy, for otherwise they will give rise to sizeable FCNC decays, which have not been observed. Indeed, the strongest bounds on the gauge boson mass coming from K-decays are usually given to be in the 10 - 100 TeV region, depending on the strength of the gauge coupling [15]. If we accept this scenario, then at energies below, say, 100 TeV, generation-changing interactions due to the exchange of these bosons will be negligible and neutrinos will interact just via the usual electroweak forces. However, at energies greater than 100 TeV, the new forces, which could in principle be strong, will come into play and give rise to new effects.

The incoming primary energy of the air showers under consideration is of order 10^{20} eV, which in collision with a proton in the air corresponds to a CM energy of around 400 TeV. They are therefore, according to the estimates of the preceding paragraph, at an energy possibly above the advent of the new interactions. Hence, neutrinos at these energies may have already acquired strong interactions. The first tenet then of our suggestion [1] is that they have and can therefore conceivably give rise to the post-GZK air showers observed.

Such a scenario, even if feasible, would of course still leave a number of burning questions unanswered. First, why should there be 3 and only 3 generations? Second, why should the symmetry be a gauge symmetry and why broken? Third, why should the new interaction be strong? And, fourth, will the cross section of the neutrino with air nuclei be large enough then to produce air showers? These questions cannot be answered in the above general framework unless supplemented by more concrete assumptions.

A particular realization of this theoretical scenario capable of answering the questions raised is afforded by a recently proposed scheme [16] based on a nonabelian generalization of electric-magnetic duality [17]. In this scheme, the generation index is identified with dual colour, from which it follows that there are exactly three generations. Further, it follows from [17] that the generation symmetry is a gauge symmetry, and from a well-known result of 't Hooft's [18] and the fact that colour is confined, that the generation symmetry is broken. Third, the broken generation symmetry is mediated by the dual gluons whose couplings are related to the usual couplings of colour gluons by the Dirac quantization condition, which in the standard conventions used in nonabelian theories with $\alpha = g^2/4\pi$ reads as [19]:

$$\tilde{g}g = 4\pi, \tag{2}$$

and are seen at these energies to be large, implying thus that the new interaction will be very strong. As to the fourth question whether neutrinos will also acquire a large enough cross section with air nuclei to give the air showers observed, this is also answered in the affirmative but requires a more detailed analysis to which we shall return later. In addition to these features, the scheme [16] gives a CKM matrix which is the identity matrix at tree level but acquires mixing only from loop corrections, which within the scheme are amenable to calculation. The values of the off-diagonal CKM matrix elements in such a calculation will in general depend on the dual gluon mass which measures the onset energy scale of the new neutrino interactions proposed. Results from a recent calculation along these lines, the details of which we intend soon to report elsewhere [20], give a good fit to the experimental CKM matrix and are consistent with a dual gluon mass of around several 100 TeV. Hence, in this scheme, not only is it possible for the neutrino to acquire strong interactions at energies above around 100 TeV as suggested in the general framework outlined above, but it seems that it is even *predicted* to be so. If that is indeed the case, then air showers initiated by neutrinos with energies greater than 10^{20} eV would occur so long as neutrinos with such energies are produced somewhere out there in the universe.

Are there viable sources? Since neutrinos are supposed to interact strongly at such energies, then any source capable of accelerating protons to these energies can produce neutrinos directly from collisions of the accelerated protons, a mechanism seemingly more efficient for high energy neutrinos than by, for example, pion decay. Now, of the three possible candidate categories of sources lying above the line:

$$BR = E/Z, \tag{3}$$

on the Hillas plot [21] (where B is the magnetic field in μG, R the size in kpc, E the energy in EeV $= 10^{18}$ eV, and $Z = 1$ for protons), which are thought capable of accelerating protons to these energies, two are thought to have difficulty emitting them [22]. For the neutron star, the accelerated proton is liable to lose its energy by sychrontron radiation on escaping simply by crossing the magnetic field which is itself responsible for its acceleration. On the other hand, for active galactic nuclei, the accelerated proton is expected to suffer energy loss in its escape by interacting with the intense radiation field thought to surround the central parts of the AGN. We notice, however, that neither of these effects would affect the neutrino, which being neutral would not interact electromagnetically and would thus be able, once it is produced by the mechanism suggested above, to escape with its energy intact.

A neutrino interacting strongly at extreme energies would even offer possible answers to several puzzling questions connected with the origin of $E > 10^{20}$ eV air showers. For instance, three pairs among the observed showers are known to have a common direction to within 2^o [23], suggesting thus a common origin for each pair. However, if they are charged particles and have different energies as these pairs do, then they ought to be deflected differently by the intervening magnetic fields and arrive with different directions unless the sources are rather close to earth. This objection, however, does not apply to neutrinos so that each pair could have come from the same distant source. Further, it has been noted that the highest energy event known, namely the 320 EeV event recorded by the Fly's Eye detector [5], points in the direction of a very powerful Seyfert galaxy (MCG 8-11-11) which is 900 Mpc away [12]. If this is taken to be the source of that particular event, then one may wonder why such a source capable of producing a 320 EeV particle should give no signal in the 10 EeV range, which could be easily detected by the Fly's Eye detector [22]. This objection, however, poses no difficulty for the neutrino which interacts strongly only at extreme energies well above 100 TeV CM. At lower energy, the interaction being there supposedly weak, neutrinos cannot, first of all, be produced directly from the collision of high energy protons as suggested above, and secondly, even if some of them are produced in MCG 8-11-11, the νN cross section would have decreased sufficiently by these energies as to give them little chance of initiating air showers when they arrive on earth.

Now, if such neutrinos are produced, by MCG 8-11-11 or some such object, then they will be able to reach us. They will be attenuated by neither the 2.7 K background photons since they are chargeless, nor by the 1.9 K background neutrinos, if massless, since their collisions will have CM energies of only around 200 MeV (even a neutrino with mass 10 eV will give only 40 GeV CM energy) at which the interaction is still very weak. But, on their arrival on earth, would they have sufficient cross sections with the air nuclei to produce showers with the observed properties, such as the above-mentioned angular and depth distributions? Because a strong interaction, though necessary, is not sufficient to guarantee a large cross section.

The answer to this crucial question would seem to be yes if generation is indeed dual colour as suggested in [16], but generally no if generation-changing interactions are mediated by gauge bosons representing an entirely new degree of freedom. The reasoning goes as follows. As is well-known, hadron cross sections are mainly governed by the sizes of the hadrons involved. In ordinary pp collisions, for example, one obtains a very reasonable estimate of around 100 mb for the total cross section if one simply pictures each proton as a greyish-black disc of radius around 1 fermi. Indeed, we know no better way than this for estimating the pp total cross section, however sophisticated. The reason that such a simple geometric picture works is because a parton in the incident proton, once it is inside the target proton, interacts with all partons of the target via long-ranged interactions so that it sees the target proton as a whole. The situation is very different from that, say, of a neutrino at ordinary high energy interacting via only electroweak forces. The range of the interaction being there given by the W mass, the neutrino will see the proton only as a collection of grey dots representing the partons inside, each with radius $1/M_W$, giving thus much smaller cross sections. Imagine now what happens if the neutrino acquires a new interaction at ultra-high energy via the exchange of some very high mass gauge bosons. If these new gauge bosons represent entirely new degrees of freedom, then the situation would be similar to the electroweak case, only now, because the interaction range is even shorter, the partons will appear as even smaller dots to the neutrino. Assuming a greater strength for the coupling will not help since it will only change the grey dots into black dots, but cannot increase the cross section beyond the unitarity limit set by the size of the dots, or in other words the interaction range. However, if one accepts that generation is dual colour as advocated in [16], then the situation is completely different. The dual colour gauge bosons, as explained in [16], do not represent a different physical degree of freedom from the ordinary colour gluons but are related to the latter by an, unfortunately rather complicated, dual transform given in loop space [17]. This fact was interpreted in physical terms in [16] as a coupling between the dual and ordinary gauge bosons and allow the former to "metamorphose" into the latter, so that on entering the target proton, the neutrino will interact at long range coherently with all partons in the target. If so, it will see the target proton not as a collection of dots but as a disc, giving thus cross sections of hadronic size.

Indeed, proceeding in this way from a geometric point of view, one can even give a rough estimate of the cross section with air nuclei for ultra-high energy neutrinos [1] 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, still appears to the nucleus as a point. Then the neutrino-nucleus cross section is simply given by the area of the nuclear disc, namely πr_A^2. Compare this now to the proton-nucleus cross section. The nucleus will still appear to the proton as a disc of radius r_A but the proton now will also appear to the nucleus as a disc of radius r_p. If these discs are black to each other, then a standard result of the geometric picture gives the cross section as $\pi(r_p + r_A)^2$. Further, assuming as often done that $r_A \sim r_p A^{1/3}$, A being the atomic number of the air nucleus which we take on the average to be say 15, we obtain from this that r_A to be about 2.47 r_p. From this we conclude that the neutrino-nucleus cross section at the ultra-high energy we are interested in would be about half the proton-nucleus cross section at the same energy.

Notice that in estimating the neutrino-nucleus cross section in the geometric picture as we did above, we have not departed from the original scheme in [16] of ascribing the new generation-changing interaction to dual colour-exchange, nor have we been shirking our duty in not trying to evaluate the cross section more properly. The fact is that hadron cross sections, involving as they do the coherent and strong interaction between the constituents, is not available to perturbative study, and we know of no better way than the geometric picture for dealing with the problem. Despite its crudeness, one beauty of the geometric picture is that it is independent of much of the details of the inter-constituent interactions, such as the coupling strength.

Nor is it dependent on the energy except through the hadron size, which was already factored out in giving the ratio of a half between the neutrino and the proton as we did above.

If the neutrino-nucleus cross section turns out to be indeed about a half of the proton-nucleus energy, then it would be sufficient to produce air showers at the sort of depth as that observed in post-GZK events. However, the estimate should be regarded at best as rough and as only an upper limit in that, depending on the dual gluon mass, the dual colour interaction may not have attained full strength yet at these energies so that the nucleus may appear as grey rather than black to the neutrino. Nevertheless, it will at least have a chance of being large enough to initiate air showers.

Suppose this is true. Is there a way to subject the idea to further experimental tests? We can think of two ways for doing so in two rather different directions.

First, as already explained above, exchanges of generation-carrying gauge bosons will give rise to flavour-changing neutral current reactions which have not so far been observed and this nonobservation has been translated into a lower bound on the gauge boson mass. Now, however, provided one accepts the hypothesis that the observed air showers with greater than 10^{20} eV energies are initiated by neutrinos then, independently of the dual colour interpretation of [16], one would obtain an upper limit of the order of around 400 TeV for the mass of the mediating gauge boson. Together with the lower limit of around 100 TeV obtained from the bounds on FCNC K-decays, these would limit the gauge boson mass within sufficiently narrow limits to make predictions of FCNC decays in other reactions meaningful. In Table 1, we list the branching ratios so predicted, assuming a unique gauge boson mass, for various FCNC decay modes of s, c, b and t particles which should be available for scrutiny at Daphne, BaBar and other strange-, charm-, bottom- and top-factory experiments now being planned. Calculations along the lines of the dual scheme of [16] will give more detailed predictions which are under investigation [24]. The observation of FCNC decays can thus provide a test, though an indirect one, for the above suggested scenario.

Another test for the hypothesis, a direct one with air showers, is also available if one takes account of the estimate given above for the neutrino cross section with air nuclei. The cross section of a primary particle with the air nucleus governs the penetration depth of the shower it initiates. Given the cross section of a particle, it is not difficult to calculate the distribution

	Theoretical Estimate	*Experimental Limit*
$Br(K^+ \to \pi^+ ll')$	$f_{s\to dll'} \left(\frac{\tilde{g}^2}{4\pi}\right)^2 2 \times 10^{-12}$	2.1×10^{-10}
$Br(K_s^0 \to ll')$	$f_{sd\to ll'} \left(\frac{\tilde{g}^2}{4\pi}\right)^2 9 \times 10^{-11}$	3.2×10^{-7}
$Br(D^+ \to \pi^+ ll')$	$f_{c\to ull'} \left(\frac{\tilde{g}^2}{4\pi}\right)^2 2 \times 10^{-13}$	1.8×10^{-5}
$Br(B^+ \to \pi^+ ll')$	$f_{b\to dll'} \left(\frac{\tilde{g}^2}{4\pi}\right)^2 10^{-10}$	3.9×10^{-3}
$Br(B^+ \to K^+ ll')$	$f_{b\to sll'} \left(\frac{\tilde{g}^2}{4\pi}\right)^2 10^{-10}$	6×10^{-5}
$\Gamma(t \to qll')$	$f_{t\to qll'} \left(\frac{\tilde{g}^2}{4\pi}\right)^2 9 \times 10^9 s^{-1}$	

Table 1: The estimates given above assume a unique mass of 400 TeV for the gauge bosons with the gauge coupling $\tilde{g}$. The coefficients f involve the mixing angles but are bounded by and of order unity. For the dual scheme of [16], $\tilde{g}$ is given by the Dirac quantization condition (2) in terms of the ordinary colour gluon coupling run to 400 TeV, and corresponds to a value for $(\tilde{g}^2/4\pi)^2$ of around 250. The resulting branching ratios satisfy the present experimental bounds but are accessible to new experiments now being planned. Detailed calculations with nondegenerate gauge boson masses and explicit f's depending on mixing angles will be reported elsewhere.

in penetration depth of the primary vertices of the air showers it initiates. For instance, inputting the proton-air nucleus cross section of about 420 mb obtained from an extrapolation of lower energy data, one easily obtains that the distribution of primary vertices would peak at around 21 km in height for a vertical shower. On the other hand, if we input a cross section of only half that size, say for the neutrino, the distribution would peak at only around 15 km in height. These statements are only weakly dependent on the energy since the cross sections on which they rely are also weakly dependent on energy. Hence, if it is really true that pre-GZK air showers are due mostly to protons and post-GZK air showers to neutrinos as we proposed, then there should be a clear distinction in the depth-distribution of primary vertices for the two categories, with the post-GZK showers clustering some 6 km lower in height compared with the pre-GZK showers. Unfortunately, in most existing detectors, except perhaps for the Fly's Eye, the height of the primary vertex of an air shower is not an easy quantity to determine. We have therefore not yet been able to ascertain whether the above prediction is correct. So far, we have found only one piece of information which may have a bearing on the matter, namely the so-called development profile given by Fly's Eye for the highest energy shower ever recorded at 3.2×10^{20} TeV. Light for this shower began to be detected at an equivalent vertical height of around 12 km. If one naively assumes that this can be identified with the primary vertex, then the shower would seem much more likely to be a neutrino as we suggested than a proton, given that the probability as calculated from the distribution of finding a proton primary vertex as low as 12 km in height is only about 5 percent [1].

Although neither of the tests suggested above can immediately be carried out, it would seem that with the new experiments being planned, for FCNC decays those already mentioned and for air showers those large projects such as Auger [7], one would have a chance to determine whether the idea that post-GZK air showers are due to neutrino is likely to be correct.

We note that although we believe that the explanation we have suggested for the post-GZK air showers is feasible, and even particularly interesting in that it is accessible to experimental tests both in air showers physics itself and in FCNC decays, we make no claim at all that it excludes other explanations. Indeed, many other explanations have already been suggested, both particle physical and astrophysical, ranging from 'gluinos' in supersymmetry to cosmic topoplogical defects, and many appear possible, so that a much deeper study is necessary before we can decide on the right one.

However, we disagree with the conclusion of a paper which has recently appeared on the hep-ph bulletin board by Burdman, Halzen and Gandhi [25] which claims sweepingly that no particle physics explanation with 'scale' > GeV is possible, excluding thus also ours presented above. Their arguments centre on the question whether the cross section would be large enough to produce the air showers observed, involving thus only particle physics and no astrophysics. In their explicit reference to our work, they based their conclusion only on a calculation of the first-order perturbative diagram exchanging a vector boson of large mass. In that case, it is obvious that the cross section of the neutrino will be much too small to explain post-GZK air showers, as already noted in our paper [1] and outlined above. For some reason, the effect of the 'metamorphosis' of the dual gluon was completely ignored which, as explained above, was the basis of our estimate of a high energy νA-cross section about one-half of that of pA. More generally, the claim in [25] of excluding almost all particle physics explanations for post-GZK air showers appears also to be based just on first-order perturbation theory and what was referred to 's-wave unitarity'. It seems to us, however, that to estimate hadronic cross sections in general, it is imperative to take account of the coherent interaction of the hadron constituents (as explained e.g. in [1]), which interaction is essentially nonperturbative and typically involves many partial waves [26]. It is therefore, to us, not at all surprising that an estimate, as that in [25], based only on s-wave unitarity and first-order perturbative calculation of the interaction between individual constituents, is unable to give a correct result.

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