lgonzalz@vxcern.cern.ch March 1997

LORENTZ INVARIANCE AND SUPERLUMINAL PARTICLES

L. GONZALEZ-MESTRES

Laboratoire de Physique Corpusculaire, Collège de France
11 pl. Marcellin-Berthelot, 75231 Paris Cedex 05 , France

and

Laboratoire d'Annecy-le-Vieux de Physique des Particules
B.P. 110 , 74941 Annecy-le-Vieux Cedex, France

Abstract

If textbook Lorentz invariance is actually a property of the equations describing a sector of matter above some critical distance scale, several sectors of matter with different critical speeds in vacuum can coexist and an absolute rest frame (the vacuum rest frame, possibly related to the local rest frame of the expanding Universe) may exist without contradicting the apparent Lorentz invariance felt by "ordinary" particles (particles with critical speed in vacuum equal to c , the speed of light). Sectorial Lorentz invariance, reflected by the fact that all particles of a given dynamical sector have the same critical speed in vacuum, will then be an expression of a fundamental sectorial symmetry (e.g. preonic grand unification or extended supersymmetry) protecting a parameter of the equations of motion.

We study the breaking of Lorentz invariance in such a scenario, with emphasis on mixing between the "ordinary" sector and a superluminal sector, and discuss with examples the consequences of existing data. The sectorial universality of the value of the high-energy speed in vacuum, even exact, does not necessarily imply that Lorentz invariance is not violated and does not by itself exclude the possibility to produce superluminal particles at accelerators or to find them in experiments devoted to high-energy cosmic rays. Similarly, the stringent experimental bounds on Lorentz symmetry violation at low energy cannot be extrapolated to high-energy phenomena. Several basic questions related to possible effects of Lorentz symmetry violation are discussed, and potential signatures are examined.

1 . INTRODUCTION

In several previous papers [1 , 6] , we discussed possible properties of a new class of superluminal particles which, contrary to tachyons [7], have positive masses and energies. Whereas the later respect Lorentz invariance and are just space-like states of "ordinary" particles (particles with critical speed in vacuum equal to c , the speed of light), the new superluminal particles would be expressions of new degrees of freedom of matter and have critical speeds in vacuum substantially different from c (in general, by several orders of magnitude). They may obey sectorial Lorentz invariances, with a critical speed $c_i \gg c$ playing the role of the space-time metric parameter for the i-th superluminal sector. While absolute space and time can perhaps be defined in an absolute rest frame (the "vacuum rest frame"), the geometry of the space-time felt by matter depends on its dynamical properties. Particles from different sectors, moving at a common velocity $\vec{\mathbf{v}} \neq 0$ with respect to the vacuum rest frame (assuming such a frame exists), will not feel the same space-time. Contrary to standard relativity, Lorentz contraction, as seen in the vacuum rest frame, will be an absolute and physically meaningful phenomenon. It will depend on the critical speed of the particle. At low energy, and as suggested by experimental tests of Lorentz invariance, we expect superluminal particles to be very weakly coupled to ordinary ones. In spite of this weak coupling, high-energy experiments (at accelerators or devoted to cosmic rays) can potentially discover the new particles (e.g. [5 , 6]) .

If the critical speed in vacuum is not an absolute expression of any intrinsic geometry of space-time, but depends (like the space-time geometry felt by the particle) on the deep dynamical properties of the matter under consideration, the fact that several particles have with great precision the same high-energy speed (i.e. the high p limit of $\nabla_{\vec{\mathbf{p}}}\ E$, where $\vec{\mathbf{p}}$ stands for momentum, E for energy and p is the modulus of $\vec{\mathbf{p}}$) in vacuum is by itself the signature of a fundamental symmetry of this sector of matter (like preonic grand unification or extended supersymmetry). If, in the vacuum rest frame, free particles obey equations of the type:

$$- A\ \partial^2\phi/\partial t^2 \ + \ iB\ \partial\phi/\partial t \ + \ \Sigma_{j=1}^{3}\ \partial^2\phi/\partial x_j^2 \ - \ D\ \phi \ = \ 0 \qquad (1)$$

where A , B and D are sectorial parameters and may be different for different particles, the possible universality of the critical speed inside a dynamical sector reflects an exact sectorial symmetry of the parameter A . The non-universality of mass inside the sector corresponds to a symmetry breaking effect acting on the parameter D . This would be perfectly compatible, for instance, with standard scenarios of supersymmetry breaking where the spontaneous breaking is a low-energy effect and leaves physics unchanged in the high-energy region above the symmetry-breaking scale. Thus, the apparent intrinsic properties of space and time, as felt by ordinary matter (experiment indicates that B is small), would just reflect the fact that the sectorial universality of A (giving the high-energy speed of particles) is preserved to a very good approximation by symmetry-breaking phenomena. The exact universality of the high-energy speed would not by itself imply exact sectorial Lorentz invariance: $B \neq 0$ violates such an invariance, but as will be seen later finite-energy effects or new Lorentz-violating terms can also arise. In what follows, we assume for simplicity that the parameter B vanishes or can be neglected.

2 . LORENTZ SYMMETRY VIOLATION

Assume that: a) each sector has a conserved sectorial symmetry broken only spontaneoulsy by a low-energy phenomenon (like standard breaking of GUTs or supersymmetry); b) all particles (or, at least, all basic constituents) belong to a single multiplet of the symmetry. If the interaction between two different sectors (the ordinary sector and a superluminal one) preserves both sectorial symmetries (but breaks the two Lorentz invariances), several possible mechanisms can be considered which we describe in a simplified way:

2a. Intrinsic violations

A typical example is provided by terms due to a possible phase transition at very high energy (see, e.g. [2 , 5]) above which Lorentz invariance, and even possibly the particles under consideration, do no longer exist. If k_i is the critical wave vector scale of the i-th superluminal sector [2] , such terms can be represented by powers of $k_i^{-2}\ \Sigma_{j=1}^{3}\ \partial^2/\partial x_j^2$ times the usual laplacian. For the ordinary particles, k_i is to be replaced by k_0 , where k_0 is the critical wave vector scale of the ordinary sector. To lowest order, in the i-th superluminal sector, we can add to (1) a term $\alpha k_i^{-2}\ (\Sigma_{j=1}^{3}\ \partial^2/\partial x_j^2)^2\ \phi$, and similarly for the ordinary sector with k_0 instead of k_i . The sectorial parameter α is expected to be of order 1 . In terms of wave function parameters, we can write in the vacuum rest frame from (1):

$$E\ =\ (2\pi)^{-1}h\ A^{-1/2}\ (k^2\ +\ D)^{1/2} \tag{2}$$

where E is the energy, $\vec{\mathbf{k}}$ the wave vector and we have taken $B\ =\ 0$ in (1). The inclusion of the new term would replace in (2) k^2 by $k^2\ (1\ +\alpha k^2\ k_i^{-2})$ if the sector is superluminal, and by $k^2\ (1\ +\alpha k^2\ k_0^{-2})$ if we are considering the ordinary sector. More generally, we can replace in (1) k^2 by $k^2\ f(\kappa)$ where $\kappa\ =\ k^2\ k_i^{-2}$ if we are dealing with a superluminal sector and $\kappa\ =\ k^2\ k_0^{-2}$ in the ordinary sector. We take $f(0)\ =\ 1$ and expect $f(\kappa)$ to exhibit a singularity in the region $\kappa \approx 1$ indicating the dissappearence of the Lorentz regime and the transition to new expressions of fundamental vacuum dynamics. If the sectorial symmetry is preserved at high energy, we expect the function $f(\kappa)$ to be universal inside each sector and not to generate any difference in critical speed between particles of the same sector. Terms involving higher t derivatives can be dealt with in a similar way.

If the sectorial symmetry remains unbroken at high energy and the value of A remains universal inside the sector under consideration, we do not expect obvious measurable effects from conventional tests of Lorentz invariance. Contrary to the scenario recently considered by Coleman and Glashow [8] , the existence of very high-energy cosmic rays does not refute the dynamics we propose. Photon decay, as well as Cherenkov radiation in vacuum by ordinary charged particles, remain forbidden for very high-energy cosmic rays as a consequence of the sectorial universality of the critical speed in vacuum. At the highest energies observed ($E\ \approx\ 10^{20}\ eV$, $k\ \approx\ 10^{25}\ cm^{-1}$), the ratio $k^2 k_0^{-2}$ is of order $\approx\ 10^{-16}$ (above the bound from [8]) for $k_0\ \approx\ 10^{-33}\ cm$. It becomes as small as 10^{-50} for $k\ \approx\ 10^8\ cm^{-1}$ (atomic distance scale). If laboratory distance and time scales are fixed from phenomena occuring at atomic or larger scales, the terms added to (1) do not seem to have a real influence on our natural definition of space and time. If they ever become detectable, they will imply a definite failure of the relativity principle [9] , as it will become impossible to write the same equations of motion in all inertial frames. A more detailed discussion of high-energy phenomena in similar situations is given in Subsection 2b.

2b. Mixing with superluminal sectors

In a previous paper [5] , we pointed out that the existence of superluminal sectors of matter is not by itself in conflict with the basic principles of standard cosmology [10] and quantum field theory (e.g. [11 - 13]) . The new superluminal particles, which have positive masses and energies, are clearly different from the previously proposed tachyons [14 , 15] and have different signatures. By definition, tachyons explicitly respect standard Lorentz invariance, whereas our superluminal particles explicitly break it. The superluminal sectors can couple to the ordinary one, but Lorentz symmetry violations related to this mixing would be very difficult to observe, as can be seen in two mixing schemes:

a) **Scheme 1 .** The two sectorial symmetries, as well as the two multiplets, are identical (an isomorphism can be spontaneously generated). Then, a unique direct mixing scheme exists for particles of different sectors and all ordinary particles undergo the same kind of mixing with the superluminal sector. In the vacuum rest frame, an ordinary particle $\mid \phi_0 >$ may mix with a superluminal one, $\mid \phi_i >$, through a hamiltonian H such that:

$$< \phi_0 \mid H \mid \phi_0 > \; = \; c\ (p^2 \; + \; m_0^2\ c^2)^{1/2} \; = \; E_0 \tag{3}$$

$$< \phi_i \mid H \mid \phi_i > \; = \; c_i\ (p^2 \; + \; m_i^2\ c_i^2)^{1/2} \; = \; E_i \tag{4}$$

$$< \phi_0 \mid H \mid \phi_i > \; = \; < \phi_i \mid H \mid \phi_0 > \; = \; \epsilon\ (p^2) \tag{5}$$

where $\vec{\mathbf{p}}$ is the momentum, p the modulus of $\vec{\mathbf{p}}$, m_0 the mass of the ordinary particle, m_i the mass of the superluminal particle and ϵ the momentum-dependent energy mixing parameter. Zero masses are preserved if $\epsilon\ (0) \; = \; 0$. The eigenvectors of H are:

$$\mid \phi > \; = \; (1 \; - \; \alpha^2)^{1/2} \; \mid \phi_0 > \; + \alpha \; \mid \phi_i > \tag{6}$$

where:

$$2\ \alpha\ \epsilon \; = \; E_i \; - \; E_0 \; - \; [(E_i \; - \; E_0)^2 \; + \; 4\ \epsilon^2]^{1/2} \tag{7}$$

corresponding to the mixed ordinary particle, with eigenvalue E given by:

$$2E \; = \; E_0 \; + \; E_i \; - \; [(E_i \; - \; E_0)^2 \; + \; 4\epsilon^2]^{1/2} \tag{8}$$

and

$$\mid \phi' > \; = \; (1 \; - \; \alpha^2)^{1/2} \; \mid \phi_i > \; - \alpha \; \mid \phi_0 > \tag{9}$$

which corresponds to the mixed superluminal particle, with eigenvalue E' satisfying:

$$2E' \; = \; E_0 \; + \; E_i \; + \; [(E_i \; - \; E_0)^2 \; + \; 4\epsilon^2]^{1/2} \tag{10}$$

In the above expressions for E and E' , the value of the square root is to be taken with the same sign as $E_i \; - \; E_0$. The speed of particle $\mid \phi >$ is given by:

$$\vec{\mathbf{v}}\ (\vec{\mathbf{p}}) \; = \; \nabla_{\vec{\mathbf{p}}}\ E \; = \; \vec{\mathbf{p}}\ [\mu(p^2)]^{-1} \tag{11}$$

where $\mu(p^2)$ is an effective mass given by:

$$[\mu(p^2)]^{-1} \ = \ 2 \ dE/dp^2 \qquad (12)$$

$\epsilon(p^2)$ breaks Lorentz symmetry and reflects unknown dynamics. If $\epsilon(p^2) \ = \ a \, p + g \ (p^2)$ where $p^{-1} \ g \ (p^2) \ \rightarrow \ 0$ as $p^2 \ \rightarrow \ \infty$, the high-energy symmetry would require the value of a to be universal inside the sector, whereas $g \ (p^2)$ can undergo the effect of low-energy symmetry breaking. Again, very high-energy cosmic rays will not exhibit phenomena like photon decay or Cherenkov emission in vacuum by charged particles. The high-energy speed of all particles in the mixed "ordinary" sector, as measured in the vacuum rest frame, will tend to v_{he} , where $2 \ v_{he} \ = \ c \ + \ c_i \ + \ [(c \ - \ c_i)^2 \ + \ 4a^2]^{1/2}$. If $c_i \ \gg \ c$ and $a \ \ll \ c_i^2$, we get $v_{he} \ \simeq \ c \ - \ a^2 c_i^{-1}$ where $c^{-1} \ (v_{he} \ - \ c)$ is of order $\approx 10^{-2}$ for $a \ \approx \ 10^2 c$ and $c_i \ \approx 10^{-6} \ c$. Scenarios involving such figures would be excluded according to recent work by Coleman and Glashow [8] if, contrary to the case we are considering, the shift in critical speed were not the same for all particles of the ordinary sector. Thus, the high-energy symmetry can play a crucial physical role which deserves further study.

For our laboratory definition of space and time, we should use the low-energy expansion of $\epsilon \ (p^2)$. Low-energy effects can be much smaller than high-energy effects if there is some high-momentum threshold contained in the p-dependence of $\epsilon(p^2)$. Assume that: a) $a \ \approx \ 10^2 \ c$ and $m_i \ c_i^2 \ \approx 1 \ TeV$; b) between atomic scales and high energies, $\epsilon(p^2)$ can be approximated by the expression: $\epsilon \ (p^2) \ \approx \ a \ p^3 \ (M^2 c_i^2 \ + \ p^2)^{-1}$ where $M_i c_i \ \approx \ 1 \ TeV/c$ is the low-momentum cut-off. At atomic scales, the energy mixing parameter ϵ will be of order $\approx 10^{-13} \ eV$ and we get a relative effect of order $\epsilon^2 \ (m_0 \ c_0^2 \ m_i \ c_i^2)^{-1} \ \approx 10^{-44}$ on the electron wave equation. Similarly, a free photon with the same values of $\epsilon \ (p^2)$ and $m_i \ c_i^2$ would undergo an energy shift of $\approx 10^{-38} \ eV$, which amounts at atomic scales to $\approx 10^{-41}$ times its energy. This does not in principle correspond to a mass, which may be even smaller, but is already below the most stringent experimental data: the p-dependence of ϵ can be made much weaker between the low-energy region and the cut-off. With the previous numbers, the photon velocity shift would be $\approx 10^{-41} \ c$ and consequently, according to formulae from [6] , we expect anisotropies in the value of the speed of light measured on earth to be below $\approx 10^{-44} \ c$ if the vacuum rest frame is close to that suggested by cosmic microwave background radiation. Part of the effect will be washed out by the redefinition of space-time automatically performed by apparatus made of mixed ordinary matter; this redefinition will in general depend on the material the apparatus is made of. The laws of physics for the mixed ordinary sector will, at such precision levels, depend on the laboratory velocity with respect to the vacuum rest frame. The mixing with the superluminal particle at atomic scales would be $\approx 10^{-25}$ and, if the interaction with the superluminal sector occurs only through direct mixing of single particles, the superluminal contribution to an electromagnetic vertex of mixed "ordinary" particles can be suppressed by an extremely small factor. For all the discussed low-energy parameters, experiment permits much higher values than those obtained with our parametrization.

Thus, the space-time geometry felt by low-energy systems made of (mixed) ordinary matter can show extremely small deviations from standard Lorentz invariance, even if a more important effect arises in the kinematics of very high-energy cosmic rays. It must also be realized that, even in the case of a small breaking of the high-energy symmetry, finite-energy effects can partially protect high-energy cosmic rays. For instance, with the above parametrization, a 10^{13} eV photon would have an anomaly in the vacuum-rest-frame E/p ratio:

$$E/p \ - \ c \ \simeq \ - \ a^2 \ c_i^{-1} \ (1 \ - \ 2p^{-2} \ c_i^2 \ M^2) \tag{13}$$

and, with the above parameters, $p^{-2} \ c_i^2 \ M^2 \ \approx \ 10^{-2}$ at $E \ \approx 10^{13} \ eV$. This term increases the energy/momentum ratio as the momentum is lowered, and ill severely limit the phase space for a photon to decay into an electron-positron pair in the presence of a very small breaking of the high-energy symmetry. The effect will be even stronger if the momentum cutoff is higher than considered in our example, and may completely protect high-energy cosmic rays up to energies much higher than those observed. Differences in speed will appear below the high-energy limit due to the finite-energy breaking of the high-energy symmetry, but will not necessarily prevent the existence of high-energy cosmic rays. The argument by Coleman and Glashow must be reconsidered in our scheme and, even in the presence of an asymptotic or finite-energy breaking of the high-energy symmetry, it leads to less stringent bounds, not better than $\delta(E/p)$ (difference in E/p ratio) $< \ 10^{-11}$ obtained assuming that a $10^{20} \ eV$ proton exchanges all its momentum with another particle. Bounds on $\delta(dE/dp)$ will be much weaker. Breaking of the speed symmetry at high energy, even by a finite energy effect, may have another important consequence: not only particles which are stable at low momentum (in the vacuum rest frame) may be unstable at high momentum (as pointed out in [8] for the photon), but conversely unstable particles may become stable when accelerated or produced at high momentum. This may have cosmological implications and eventually be tested by high-energy experiments.

At $p \ \approx \ 1 \ TeV/c$ and with the above figures, we have $\epsilon \ (p^2) \ \approx \ 10^{-2} \ TeV$ and a mixing parameter $\approx \ 10^{-4}$ between ordinary and superluminal particles, which means that the probability for two mixed quarks with TeV/c momenta to simultaneoulsy turn into superluminal particles is $\approx \ 10^{-16}$ (not necessarily negligible at LHC luminosities). Similarly, the probability for a hard virtual particle produced at LHC to become superluminal would be $\approx \ 10^{-8}$, which again cannot be entirely disregarded. Apart from direct production of superluminal particles, precision speed measurements for muons and protons at LHC energies deserve consideration. Finally, it may be worth noticing that a mixing $\alpha \ \approx \ 10^{-4}$ in the ordinary sector would lead to interaction probabilites slightly lower than expected, typically by a fraction $\approx \ 10^{-3}$, and similarly for energy loses. In the presence of interference phenomena, the effect may become larger.

b) **Scheme 2 .** If symmetries or multiplets are different and direct mixing between single particles from different sectors is forbidden, mixing between the two sectors can still arise, for instance, through insertions of pairs of superluminal lines inside self-energy graphs. In this case, the energy of an ordinary particle can be written in terms of its momentum as:

$$E \ (p) \ = \ (p^2 \ + \ m^2)^{1/2} \ + \ \Sigma \ (p^2) \tag{14}$$

where the first term ignores the mixing with the superluminal sector and $\Sigma \ (p^2)$ contains the superluminal insertions. As before, we can write $\Sigma \ (p^2) \ = \ s \ p \ + \ t \ (p^2)$, where

$p^{-1}\ t\ (p^2)\ \rightarrow\ 0$ as $p\ \rightarrow\ \infty$, and (using the high-energy symmetry) require the value of s to be universal inside the sector while $t\ (p^2)$ can reflect the low-energy symmetry breaking.

Arguments similar to scheme 1 can then be developed, and again with the same philosophy we may expect very small numbers in direct searches for Lorentz invariance violations at low energy even if high-energy effects turn out to be detectable. A particularly interesting possibility would be that the Higgs boson couples to a superluminal scalar through a ϕ^4 term in the lagrangian (the squared modulus of the Higgs field times the squared modulus of the superluminal scalar field like in [1]), and that the superluminal boson has a rest energy in the TeV range. Then, the new physics expected at TeV scales on the grounds of Higgs theory considerations could directly involve the production of pairs of superluminal particles, together with other departures from the standard model.

3. DIRECT SEARCH FOR SUPERLUMINAL PARTICLES

With the same figures as before, LHC collisions can potentially involve interactions between superluminal components of the high-energy particles. To the already specified suppression factors, we may be led to add phase space limitations. If, for instance, $c_i\ \approx\ 10^6\ c$ as before, naive on-shell kinematics would require the momenta of the incoming quarks to cancel with 10^{-6} precision if superluminal particles must emerge from the collision (otherwise, there would not be enough energy left to produce the free superluminal particles). We would then expect a strong extra supression factor from these considerations, although our lack of knowledge of the dynamics of superluminal particles prevents us from formulating definite conclusions (for instance, some dramatic effect might be generated by a pair of strongly off-shell superluminal particles). On the other hand, going beyond point-like field theory, it should be noticed that Lorentz contraction of ordinary particles may modify their direct mixing with the superluminal sector (see [6] on the absolute physical meaning of Lorentz contraction and its matter-dependence), as it modifies the relative longitudinal size between ordinary and superluminal particles. If superluminal particles are smaller by orders of magnitude than ordinary ones (which would most likely occur if $k_i\ \gg\ k_0$), Lorentz contraction of ordinary particles may lead to further enhancement of direct coupling between particles from the two sectors. Such effects are new with respect to coventional particle physics, where Lorentz contraction is a relative phenomenon. The situation would even become more favourable in future generations of higher-energy accelerators. In the case of direct mixing, the mixing parameter α will reach its asymptotic value only well above the rest energy $m_i c_i^2$ of the superluminal particle under consideration. In any case, it seems that some scenarios with superluminal particles can be explored by LHC experiments, mainly for values of c_i between c and $10^6\ c$. We shall not attempt to give here a general parametrization, but obvious examples can be built, especially for critical speeds in vacuum one or two orders of magnitude above c . Beam quality will play a crucial role to precisely define these potentialities.

High-energy cosmic rays of the superluminal sector under consideration would satisfy modified versions of the GZK cutoff [16] allowing for higher energies and larger source distances, and possibly reach cosmic ray detectors on earth, like AMANDA [17]. Particles from other superluminal sectors, more weakly coupled to ordinary matter, would be much less contrained by the GZK cutoff. The main limitation for a superluminal cosmic ray to be able to reach earth is likely to come from "Cherenkov" radiation (i.e. the emission of particles belonging to a sector with lower critical speed) in vacuum. However, if superluminal matter is very abundant in the Universe, this abundance may generate other cutoffs of the GZK type for superluminal particles. The superluminal particles possibly produced at accelerators will in general not be the same that we can observe in cosmic ray detectors, especially if several superluminal sectors of matter exist. The fact that very high-energy ordinary particles may undergo mixing with superluminal sectors is potentially a motivation for detailed measurements (e.g. speed, "Cherenkov" emission in vacuum even at small rates...) in high-energy cosmic-ray detectors.

We therefore claim that the impressive results of low-energy searches for Lorentz symmetry violation at low energy, excluding such phenomena down to very small numbers (e.g. [18 , 19]), do really not allow to conclude against the potentialities of the search for superluminal particles in high-energy experiments. On the contrary, high-energy experiments may indeed be the only way to find evidence for Lorentz symmetry violation, as well as for the existence of superluminal sectors. As stressed in our previous papers (e.g. [1, 5]), the observed stability of Lorentz invariance in the low-energy region and the possible discovery of superluminal particles in high-energy experiments are not really incompatible, since Lorentz symmetry violation would be essentially related to phenomena occuring at very high energy and very short distance scales. Massless ordinary particles may even have different low-energy and high-energy speeds in vacuum, as discussed above.

Signatures in high-energy experiments are a crucial point: can we identify superluminal particles in such experiments? Cherenkov radiation in vacuum (e.g. the emission of ordinary particles by the produced superluminal ones) may be a crucial signature in many cases. At accelerators, its structure and energy dependence would be easy to identify. In cosmic ray experiments, it may be detectable even if the particle couples very weakly to ordinary matter. Ordinary cosmic rays resulting from this emission can reach the detector, even if the superluminal particle does not. Then, the event could most likely not by explained in terms of known astrophysical sources. In all cases, because of the very high energy/momentum ratio in the new dynamical sector, "Cherenkov" radiation in vacuum by superluminal particles will present special features. At an angle of $\pi/2$ with respect to its momentum, a relativistic superluminal particle (i.e. at speed $v_i \sim c_i$) with momentum p_i and energy E_i in the vacuum rest frame can emit an ordinary particle with energy $E \approx E_i\ c^2\ c_i^{-2}$ and momentum $p \approx E_i\ c\ c_i^{-2} \simeq p_i\ c\ c_i^{-1}$. This is the highest possible momentum of an emitted single particle. The longitudinal momentum of emitted single particles, with respect to the direction of motion of the superluminal particle, is strongly limited. Cherenkov radiation in vacuum will most likely be mainly made of very heavy virtual particles quickly decaying into pairs of jets (hadronic or leptonic) back-to-back in order to account for the small momentum left. Conversion of these vacuum-rest-frame figures to the laboratory rest frame can be made according to formulae developed in [6] .

Other signatures exist as well and can be explored. As stressed in previous papers [5 , 6] , if a high-energy superluminal cosmic ray undergoes a hard interaction inside the detector releasing a sizeable part of its energy, we expect in most cases the production of two jets "back-to-back" due to energy and momentum conservation. Furthermore, the event distribution would be nearly isotropic as a result of the relation between the energy and momentum of the superluminal particle. Such a signature would be unambiguous, even at very small event rate. Similarly, precise timing in accelerator experiments may provide dramatic signatures [6]. Absolute time resolution below 10^{-8} s would in principle allow to directly notice a speed well above c in a 10 m detector.

4. NEUTRINO AND OSCILLATION SIGNATURES

As previoulsy suggested in our papers [1 - 6] , and discussed by Coleman and Glashow in their recent study [8] , a small violation of Lorentz invariance may lead to observable effects in neutrino physics. The numbers obtained above do not allow, in our scenario, to exclude Lorentz symmetry violation from low-energy neutrino data, but make further experiments particularly relevant and necessary. Furthermore, other particles than neutrinos can undergo velocity oscillations, especially at high energy, if such oscillations are allowed.

Due to the existence of a preferred frame and to the intrinsic meaning of velocity with respect to this frame, there is a real physical difference between oscillations and high and low momenta. A high-energy particle is intrinsically different from a low-energy particle: no Lorentz transformation can make them completely equivalent. Exclusion plots for oscillations should include momentum-dependence if Lorentz invariance is broken, as they test different physical objects when the speed is modified. While low-energy and nuclear physics experiments can test important aspects of neutrino oscillations, including Lorentz invariance, these phenomena are not necessarily the same that can be potentially uncovered by high-energy experiments. Also, in scenarios like that of Subsection 2b , Scheme 1 , the global high-energy symmetry is preserved but gauge symmetries become sectorial and approximate when mixing between the two sectors is introduced. Therefore, high-energy experiments may indeed be able to test new physics related to this mixing.

If the above high-energy symmetry undergoes a small breaking leading to differences in high-energy speeds escaping the Coleman-Glashow constraints (e.g. Subsection 2b , Scheme 1), the experimental consequences can be important even if very high-energy cosmic rays (e.g. protons and photons) remain allowed. At TeV energies, and assuming masses to be small enough (typically, $\delta m^2\ c^5\ sin2\theta_m \ll E^2\ \delta v\ sin2\theta_v$, where E is the energy , m^2 the difference in squared mass, θ_m the mass mixing angle and θ_v the velocity mixing angle [8]), with a velocity symmetry breaking $\delta v\ v^{-1}\ \approx\ 10^{-19}$, oscillation would occur at the scale of the detector size for all produced ordinary particles able to oscillate. Well above this value of $\delta v\ v^{-1}$, the mixing would be full. Such considerations are not only relevant for neutrinos: for instance, mixing with the superluminal sector at high momentum may result in high-energy mixing between charged leptons. In this case, the oscillation will depend on the details of the p-dependence of the mixing (which reflects in turn unknown details of dynamics inside the superluminal sector). Again, the mixing can be very small at low energy but significant at high energy, similar to Subsection 2b . LHC and cosmic ray experiments may be able to put relevant bounds on such phenomena.

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