POSSIBLE EFFECTS OF LORENTZ SYMMETRY VIOLATION ON THE INTERACTION PROPERTIES OF VERY HIGH-ENERGY COSMIC RAYS

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ABSTRACT
Special relativity has been tested at low energy with great accuracy, but these results cannot be extrapolated to the very high-energy region. Introducing a critical distance scale, \(a\), below \(10^{-25} \text{ cm}\) (the wavelength scale of the highest-energy observed cosmic rays) allows to consider models, compatible with standard tests of special relativity, where a small violation of Lorentz symmetry (\(a\) can, for instance, be the Planck length \(\approx 10^{-33} \text{ cm}\)) produces dramatic effects on the interaction properties of very high-energy particles. Lorentz symmetry violation may potentially solve all the basic problems raised by the highest-energy cosmic rays (origin and energy, propagation...). Furthermore, superluminal sectors of matter may exist and release very high-energy ordinary particles or directly produce very high-energy cosmic-ray events with unambiguous signatures in very large detectors. We discuss these phenomena, as well as the cosmic-ray energy range (well below the energy scale associated to the fundamental length) and experiments where they could be detected and studied.

LORENTZ SYMMETRY VIOLATION BY NONLOCAL DYNAMICS

It is a common prejudice that Lorentz invariance may cease to be valid at Planck energy, but the consequences of this possibility for physics at lower energy scales remain basically unexplored. Contrary to superficial appearance, such a phenomenon would indeed play a crucial role at energies well below Planck scale. In particular, important observable effects can be predicted at the energy scale of the highest-energy cosmic rays. In previous papers (Gonzalez-Mestres, 1997a and 1997b), we suggested that, as a consequence of nonlocal dynamics at Planck scale or at some other fundamental length scale, Lorentz symmetry violation can result in a modification of the equation relating energy and momentum which would write in the vacuum rest frame:

\[
E = (2\pi)^{-1} h c a^{-1} e (k a) \tag{1}
\]

where \(E\) is the energy of the particle, \(h\) the Planck constant, \(c\) the speed of light, \(a\) the fundamental length scale, \(k\) the wave vector modulus and \([e (k a)]^2\) is a convex function of \((k a)^2\) obtained from nonlocal vacuum dynamics. Rather generally, we find that, at wave vector scales below the inverse of the fundamental length scale, Lorentz symmetry violation in relativistic kinematics can be parameterized writing:

\[
e (k a) \simeq [(k a)^2 - \alpha (k a)^4 + (2\pi a)^2 h^{-2} m^2 c^2]^{1/2} \tag{2}
\]

where \(\alpha\) is a positive constant between \(10^{-1}\) and \(10^{-2}\). At high energy, we can write:

\[
e (k a) \simeq k a [1 - \alpha (k a)^2/2] + 2 \pi^2 h^{-2} k^{-1} a m^2 c^2 \tag{3}
\]

and, in any case, we expect observable kinematical effects when the term \(\alpha (ka)^3/2\) becomes as large as the term \(2 \pi^2 h^{-2} k^{-1} a m^2 c^2\). For a proton at \(E \approx 10^{20} \text{ eV}\) and with \(a \approx 10^{-33} \text{ cm}\), one would have:

\[
\alpha (k a)^2/2 \approx 10^{-18} \gg 2 \pi^2 h^{-2} k^{-2} m^2 c^2 \approx 10^{-22} \tag{4}
\]
CONSEQUENCES OF THE NEW KINEMATICS

Particles at the wavelength scale of the highest-energy cosmic rays would be sensitive to the new kinematics. If \( \alpha \) were negative, all particles would become unstable at these energies, more precisely at energies above \( E \approx (2\pi)^{-1/2} \alpha^{-1/4} (m c^3 h a^{-1})^{1/2} \). For instance, if \( c \) and \( \alpha \) had universal values for all particles and \( \alpha \) were negative, and taking \( a \approx 10^{-33} \text{ cm} \), a proton with energy above \( \approx 10^{19} \text{ eV} \) would decay into a proton of lower energy and one or several photons, or into a neutron or a proton plus pions, or by emitting particle-antiparticle pairs. Similar considerations would apply to electrons above \( \approx 10^{17} \text{ eV} \). The unstability of very high-energy particles would not disappear if the value of \( \alpha \), although negative, were not universal. Any very high-energy particle with \( \alpha < 0 \) could always decay by emitting its own particle-antiparticle pairs, even if \( c \) were not universal (in this Section, we naturally assume the breaking of the universality of \( c \) to be a rather small effect). With \( \alpha = 0 \), some very high-energy particles would become unstable if \( c \) were not universal whereas others would remain stable (Coleman and Glashow, 1997); but, if \( \alpha \neq 0 \), new mechanisms arise (Gonzalez-Mestres, 1997a and 1997b) which compete with that considered by Coleman and Glashow and, due the wavelength dependence of nonlocal effects, dominate over the Coleman-Glashow (CG) mechanism at high enough energy. With \( \alpha > 0 \) for all particles, the effect of the term \( -\alpha (k a)^2 / 2 \) dominates over the CG mechanism at very high energy, even if the value of \( \alpha \) is not universal.

If \( c \) and \( \alpha \) have universal values, and \( \alpha \) is positive, and taking the Planck length to be the fundamental distance scale, the following new effects arise:

- a) The Greisen-Zatsepin-Kuzmin (GZK) cutoff on very high-energy cosmic protons and nuclei (Greisen, 1966; Zatsepin and Kuzmin, 1966) does no longer apply (Gonzalez-Mestres, 1997a and 1997b). Very high-energy cosmic rays originating from most of the presently observable Universe can reach the earth and generate the highest-energy detected events.

- b) Unstable particles with at least two massive particles in the final state of all their decay channels become stable at very high energy (Gonzalez-Mestres, 1997a and 1997b). In any case, unstable particles live longer than naively expected with exact Lorentz invariance and, at high enough energy, the effect becomes much stronger than previously estimated for nonlocal models (Anchordoqui, Dova, Gómez Dumm and Lacentre, 1997) ignoring the small violation of relativistic kinematics.

- c) The allowed final-state phase space of two-body collisions is seriously modified at very high energy, especially when, in the vacuum rest frame where expressions (1) - (3) apply, a very high-energy particle collides with a low-energy target (Gonzalez-Mestres, 1997c). Energy conservation reduces the final-state phase space at very high energy and can lead to a sharp fall of cross sections starting at incoming-particle wave vectors well below the inverse of the fundamental length.

- d) In astrophysical processes, the new kinematics may inhibit phenomena such as GZK-like cutoffs, photodisintegration of nuclei, decays, radiation emission under external forces, momentum loss (which at very high energy does not imply deceleration) through collisions, production of lower-energy secondaries... potentially solving all the basic problems raised by the highest-energy cosmic rays (Gonzalez-Mestres, 1997c). Due to the fall of cross sections, energy losses become much weaker than expected with relativistic kinematics and astrophysical particles can be pushed to much higher energies; similarly, they will be able to propagate to much longer astrophysical distances, and many more possible sources (in practically all the presently observable Universe) can be considered for very high-energy cosmic rays reaching the earth; as particle lifetimes are much longer, new possibilities arise for the nature of these cosmic rays. The same considerations apply to nuclei.
superluminal particles with positive mass and energy and critical speed in vacuum $c_i > c$ ($c =$ speed of light), have been considered in previous papers (Gonzalez-Mestres, 1996 and 1997d). They can be associated to new dynamical sectors where, for the $i$-th sector, a Lorentz symmetry exists with critical speed parameter $c_i$. Mixing between different dynamical sectors would break these Lorentz invariances, including the ”ordinary” one (i.e. that of standard relativity, with critical speed parameter equal to $c$). Superluminal particles can have very large rest energies due to the relation $E = mc_i^2$ (Gonzalez-Mestres, 1996 and 1997d), and produce very high-energy ”ordinary” cosmic rays through astrophysical processes, decays, collisions or ”Cherenkov” radiation in vacuum (spontaneous emission of particles with lower critical speed). They can also reach the earth and produce inelastic events in very large-volume detectors: then, due to energy and momentum conservation and to the relation $E \approx c_i p \gg c p$, an incoming superluminal particle of energy $E$, momentum $p$ and critical speed in vacuum $c_i$ would originate two very high-energy showers with
Almost exactly equal energy and momentum, and almost exactly “back-to-back” (Gonzalez-Mestres, 1996 and 1997d). The situation is similar for spontaneous "Cherenkov" emission. Underground or underwater very large-volume detectors would be able to unambiguously identify such events, even at extremely low rate. But, for very high-energy events, a very well-suited "large-volume" detector would also be the AUGER observatory (AUGER Collaboration, 1997), which will most likely offer the largest available target (the atmosphere over a uniquely large surface) and where unconventional events will develop atypical cascade development profiles, again providing unambiguous signatures.

CONCLUDING REMARKS
Future experiments devoted to ultra-high energy cosmic rays will provide unique tests of possible Lorentz symmetry violation at scales unaccessible to standard tests, and be sensitive to possible departures from the Poincaré relativity principle (Poincaré, 1905) at very small distances. At least two kinds of phenomena violating this principle deserve serious consideration: a) nonlocal effects at Planck scale or at some other fundamental length scale; b) interaction with superluminal sectors of matter. In the first case, the behaviour of ”ordinary” particles will be modified. In the second case, we can try to directly discover the superluminal particles. Contrary to general prejudice, a violation of Lorentz symmetry at distance scale \( \approx a \) does not require energies close to \( \approx (2\pi)^{-1} h c a^{-1} \) to produce observable effects at leading level. Assuming \( c \) and \( \alpha (\alpha > 0) \) to have universal values, cosmic ray data suggest \( a \) to be in the range \( 10^{-35} \text{ cm} < a < 10^{-30} \text{ cm} \) (Gonzalez-Mestres, 1997c). Superluminal particles can produce very high-energy events in very large-surface or very large-volume detectors: future experiments should consider their possible existence. Very high-energy ”ordinary” cosmic rays may also have been released by cosmic superluminal particles. Very high-energy interactions (as measured in the vacuum rest frame) in astrophysical processes, as well as in cosmic-ray propagation and in cosmic-ray detectors, are the key to possibly uncover and identify this new physics.

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