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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} *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 $\approx 10^{-33}$ *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 α 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 $E \,\approx\, 10^{20}\, eV$ and with $a \,\approx\, 10^{-33}\, cm$, one would have:

$$\alpha\,(k\,a)^2/2 \;\approx\; 10^{-18} \;\gg\; 2\,\pi^2\, h^{-2}\, k^{-2}\, m^2\, c^2 \;\approx 10^{-22} \tag{4}$$

so that, although $\alpha(ka)^3/2$ is indeed very small as compared to the value of $e\ (k\ a)$, the term $2\ \pi^2\ h^{-2}\ k^{-1}\ a\ m^2\ c^2$ represents an even smaller fraction of this quantity. We therefore expect corrections to relativistic kinematics to play a crucial role at the highest cosmic ray energies, well below the energy scale associated to the inverse of the fundamental length. In what follows, we make the crucial assumption that the earth is moving slowly with respect to the vacuum rest frame.

CONSEQUENCES OF THE NEW KINEMATICS

Particles at the wavelentgth scale of the highest-energy cosmic rays would be sensitive to the new kinematics. If α 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 α had universal values for all particles and α were negative, and taking $a\ \approx\ 10^{-33}\ cm$, a proton with energy above $\approx\ 10^{19}\ eV$ 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 $\approx\ 10^{17}\ eV$. The unstability of very high-energy particles would not disappear if the value of α , 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 be 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 α is not universal.

If c and α have universal values, and α 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 longuer 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.

e) If the new kinematics can explain the existence of $\approx 10^{20}\ eV$ events, it also predicts that, above some higher energy scale (around $\approx 10^{22}\ eV$ for $a \approx 10^{-33}\ cm$), the fall of cross sections will prevent the cosmic ray from depositing most of its energy in the atmosphere (Gonzalez-Mestres, 1997c). Such extremely-high energy particles will produce atypical events of apparently much lower energy. New analysis of data and experimental designs are required to explore this possibility.

To be complete, our discussion must also consider situations where α is positive, but its value is not universal. This could be the case, for instance, if the composite character of nucleons and nuclei prevents them from being described as "elementary" single particles when deriving expressions like (1) - (3). Due to the loss of Lorentz invariance, it is far from obvious how to extrapolate to Planck scale the low-energy bound-state structure: the rest structure of the composite object will depend on its speed with respect to the vacuum rest frame. The value of α may depend on this dynamics.

In a parton-like picture, we could be led to $\alpha \approx 0.05$ for quarks, leptons and gauge bosons, ≈ 0.01 for mesons, ≈ 0.005 for nucleons and $\approx 0.05\ (3A)^{-2}$ for a nucleus with A nucleons. Such a kinematics implies upper bounds on the allowed energy of a stable nucleon or nucleus (above some energy, spontaneous emission of photons or electron-positron pairs is kinematically allowed). In this case, with $a \approx 10^{-33}\ cm$ and assuming a universal value of c , cosmic ray events above $\approx 10^{19}\ eV$ cannot be protons, and above $\approx 10^{20}\ eV$ they cannot be nuclei. It may be tempting to try to tune the model in such a way that the maximum allowed energy for cosmic nuclei coincides with that of the most energetic observed cosmic ray event (around $3.10^{20}\ eV$). Among the parameters of the fit would be the fundamental length a and, for each particle, the values of c and α . A more unconventional approach would be to attribute events above $\approx 10^{20}\ eV$ to other kinds of cosmic particles. For instance, at $E \approx 10^{18}\ eV$ and with $a \approx 10^{-33}\ cm$, a muon would have a lifetime $\approx 10^4\ s$ according to standard relativity; but, in the model we are considering, Lorentz symmetry violation would reduce the phase space of its decay products at this energy scale, and more and more strongly as energy increases (Gonzalez-Mestres, 1997a and 1997b). It is not excluded that, in very high astrophysical magnetic fields, muons can live long enough to be pushed to ultra-high energies. Becoming very long-lived with the help of Lorentz symmetry violation and keeping their energy with the help of the fall of electromagnetic cross sections (Gonzalez-Mestres, 1997c), they may subsequently reach the earth. When studying the event shape in detectors, it should also be kept in mind that, at such energies never reached by accelerators, new interaction properties may develop.

In general, if α is positive but does not have a universal value, precise numerical studies are required for each specific scenario, but candidates to the highest-energy cosmic-ray events seem to exist in most cases. It is remarkable that future experiments devoted to ultra-high energy cosmic rays will indeed be able to test models involving Lorentz symmetry violation at Planck scale and discriminate between different scenarios, using the shape and spectra of cosmic-ray events.

SUPERLUMINAL PARTICLES

Superbradyons, i.e. superluminal particles with positive mass and energy and critical speed in vacuum $c_i \gg c$ (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 $E \simeq c_i\ p \gg cp$, 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 $\approx (2\pi)^{-1} \hbar c a^{-1}$ to produce observable effects at leading level. Assuming c and α ($\alpha > 0$) to have universal values, cosmic ray data suggest a to be in the range $10^{-35}\ cm < a < 10^{-30}\ cm$ (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.

REFERENCES

Anchordoqui, L., Dova, M.T., Gómez Dumm, D. and Lacentre, P., *Zeitschrift für Physik C* 73 , 465 (1997).

AUGER Collaboration, "The Pierre Auger Observatory Design Report" (1997).

Coleman, S. and Glashow, S.L., "Cosmic Ray and Neutrino Tests of Special Relativity", paper hep-ph/9703240 of LANL (Los Alamos) electronic archive (1997).

Gonzalez-Mestres, L., "Physical and Cosmological Implications of a Possible Class of Particles Able to Travel Faster than Light", contribution to the 28^{th} International Conference on High-Energy Physics, Warsaw July 1996 . Paper hep-ph/9610474 of LANL electronic archive (1996).

Gonzalez-Mestres, L., "Vacuum Structure, Lorentz Symmetry and Superluminal Particles", paper physics/9704017 of LANL electronic archive (1997a).

Gonzalez-Mestres, L., "Absence of Greisen-Zatsepin-Kuzmin Cutoff and Stability of Unstable Particles at Very High Energy, as a Consequence of Lorentz Symmetry Violation", contribution HE 1.2.36 to the 25-th International Cosmic Ray Conference. Paper physics/9705031 of LANL electronic archive (1997b).

Gonzalez-Mestres, L., "Lorentz Symmetry Violation and Very High-Energy Cross Sections", contribution to the International Conference on Relativistic Physics and some of its Applications, Athens June 1997 . Paper physics/9706022 of LANL electronic archive (1997c).

Gonzalez-Mestres, L., "Superluminal Particles and High-Energy Cosmic Rays", contribution HE 1.2.35 to the 25-th International Cosmic Ray Conference. Paper physics/9705032 of LANL electronic archive (1997d).

Greisen, K., *Phys. Rev. Lett.* 16 , 748 (1966).

Kirzhnits, D.A., and Chechin, V.A., *Soviet Journal of Nuclear Physics*, 15 , 585 (1972).

Poincaré, H., Speech at the St. Louis International Exposition of 1904 , *The Monist 15* , 1 (1905).

Zatsepin, G.T. and Kuzmin, V.A., *Pisma Zh. Eksp. Teor. Fiz.* 4 , 114 (1966).