Deformed Lorentz Symmetry and Ultra-High Energy Cosmic Rays

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Abstract

Lorentz symmetry violation (LSV) is often discussed using models of the $TH\epsilon\mu$ type which involve, basically, energy independent parameters. However, if LSV is generated at the Planck scale or at some other fundamental length scale, it can naturally preserve Lorentz symmetry as a low-energy limit (deformed Lorentz symmetry, DLS). Deformed relativistic kinematics (DRK) would be consistent with special relativity in the limit k (wave vector) $\rightarrow\ 0$ and allow for a deformed version of general relativity and gravitation. We present an updated discussion of the possible implications of this pattern for cosmic-ray physics at very high energy. A $\approx\ 10^{-6}$ LSV at Planck scale, leading to a DLS pattern, would potentially be enough to produce very important observable effects on the properties of cosmic rays at the $\approx\ 10^{20}\ eV$ scale (absence of GZK cutoff, stability of unstable particles, lower interaction rates, kinematical failure of the parton model...). We compare our approach with more recent similar claims made by S. Coleman and S. Glashow from models of the $TH\epsilon\mu$ type.

1 Status of Special Relativity

A basic physics issue underlies the priority debate: who was (were) the author(s) of the special relativity theory? It clearly turns out that historical arguments are biased by physical prejudices and interpretations.

H. Poincaré was the first author to consistently formulate the relativity principle stating (Poincaré, 1895): *"Absolute motion of matter, or, to be more precise, the relative motion of weighable matter and ether, cannot be disclosed. All that can be done is to reveal the motion of weighable matter with respect to weighable matter"*. He further emphasized the deep meaning of this law of Nature when he wrote (Poincaré, 1901): *"This principle will be confirmed with increasing precision, as measurements become more and more accurate"*.

Several authors have emphasized the role of H. Poincaré in building relativity and the relevance of his thought (Logunov, 1995 and 1997; Feynmann, Leighton, & Sands, 1964). In his June 1905 paper (Poincaré, 1905), published before Einsteins's article (Einstein, 1905) arrived (on June 30) to the editor, he explicitly wrote the relativistic transformation law for the charge density and velocity of motion and applied to gravity the "Lorentz group", assumed to hold for "forces of whatever origin". But his priority is sometimes denied on the grounds that *"Einstein essentially announced the failure of all ether-drift experiments past and future as a foregone conclusion, contrary to Poincaré's empirical bias"* (Miller, 1996), that Poincaré did never *"disavow the ether"* (Miller, 1996) or that *"Poincaré never challenges... the absolute time of newtonian mechanics... the ether is not only the absolute space of mechanics... but a dynamical entity"* (Paty, 1996). It is implicitly assumed that A. Einstein was right in 1905 when *"reducing ether to the absolute space of mechanics"* (Paty, 1996) and that H. Poincaré was wrong because *"the ether fits quite nicely into Poincaré's view of physical reality: the ether is real..."* (Miller, 1996). In fact, there is no scientific evidence for such an assumption.

Modern particle physics has brought back the concept of a non-empty vacuum where free particles propagate: without such an "ether" where fields can condense, the standard model of electroweak interactions could not be written and quark confinement could not be understood. Modern cosmology is not incompatible with an "absolute local frame" close to that suggested by the study of cosmic microwave background radiation. Therefore, the "ether" may well turn out to be a real entity in the *XXI-th* century physics and astrophysics. Then, the relativity principle would become a symmetry of physics, a concept whose paternity was attributed to H. Poincaré by R.P. Feynman (as quoted by Logunov, 1995): *"Precisely Poincaré proposed investigating what could be done with the equations without altering their form. It was precisely his idea to pay attention to the symmetry properties of the laws of physics"*.

As symmetries in particle physics are in general violated, Lorentz symmetry may be broken and an absolute local rest frame may be detectable through experiments performed beyond some critical scale. Poincaré's special relativity (a symmetry applying to physical processes) could live with this situation, but not Einstein's approach such as it was formulated in 1905 (an absolute geometry of space-time that matter cannot escape). But, is Lorentz symmetry broken? We discuss here two issues: a) the scale where we may expect Lorentz symmetry to be violated; b) the physical phenomena and experiments potentially able to uncover Lorentz symmetry violation (LSV). Previous papers on the subject are (Gonzalez-Mestres, 1998a, 1998b and 1998c) and references therein. We have proposed that Lorentz symmetry be a low-energy limit, broken following a k^2-law (k = wave vector) between the low-energy region and some fundamental energy (length) scale.

2 Lorentz Symmetry As a Low-Energy Limit

Low-energy tests of special relativity have confirmed its validity to an extremely good accuracy, but the situation at very high energy remains more uncertain. If Lorentz symmetry violation (LSV) follows a E^2 law (E = energy), similar to the effective gravitational coupling, it can be $\approx\ 1$ at $E\ \approx\ 10^{21}\ eV$ and $\approx\ 10^{-26}$ at $E\ \approx\ 100\ MeV$ (corresponding to the highest momentum scale involved in nuclear magnetic resonance experiments), in which case it will escape all existing low-energy bounds (deformed Lorentz symmetry, DLS). If LSV is $\approx\ 1$ at Planck scale ($E\ \approx\ 10^{28}\ eV$), and following a similar law, it will be $\approx\ 10^{-40}$ at $E\ \approx\ 100\ MeV$. Our suggestion is not in contradiction with Einstein's thought such as it became after he had developed general relativity. In 1921 , A. Einstein wrote in "Geometry and Experiment" (Einstein, 1921): *"The interpretation of geometry advocated here cannot be directly applied to submolecular spaces... it might turn out that such an extrapolation is just as incorrect as an extension of the concept of temperature to particles of a solid of molecular dimensions"*. It is remarkable that special relativity holds at the attained accelerator energies, but there is no fundamental reason for this to be the case above Planck scale.

A typical example of patterns violating Lorentz symmetry at very short distance is provided by nonlocal models where an absolute local rest frame exists and non-locality in space is introduced through a fundamental length scale a where new physics is expected to occur (Gonzalez-Mestres, 1997a). Such models lead to a deformed relativistic kinematics (DRK) of the form (Gonzalez-Mestres, 1997a and 1997b):

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

where h is the Planck constant, c the speed of light, k the wave vector and $[e\ (k\ a)]^2$ is a convex function of $(k\ a)^2$ obtained from vacuum dynamics. Such an expression is equivalent to special relativity in the small k limit. Expanding equation (1) for $k\ a\ \ll\ 1$, we can write (Gonzalez-Mestres, 1997a and 1997c):

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

α being a model-dependent constant, in the range $0.1\ -\ 0.01$ for full-strength violation of Lorentz symmetry at the fundamental length scale, and *m* the mass of the particle. For momentum $p\ \gg\ mc$, we get:

$$E\ \ \simeq\ \ p\ c\ +\ m^2\ c^3\ (2\ p)^{-1}\ -\ p\ c\ \alpha\ (k\ a)^2/2 \tag{3}$$

The "deformation" $\Delta\ E\ \ =\ \ -\ p\ c\ \alpha\ (k\ a)^2/2$ in the right-hand side of (3) implies a Lorentz symmetry violation in the ratio $E\ p^{-1}$ varying like $\Gamma\ (k)\ \simeq\ \Gamma_0\ k^2$ where $\Gamma_0\ \ =\ -\ \alpha\ a^2/2$. If c is a universal parameter for all particles, the DRK defined by (1) and (2) preserves Lorentz symmetry in the limit $k\ \rightarrow\ 0$, contrary to the standard $TH\epsilon\mu$ model (Will, 1993). If α is universal, LSV does not lead (Gonzalez-Mestres, 1997a, c and e) to the spontaneous decays predicted in (Coleman, & Glashow, 1997 and subsequent papers). On more general grounds, as we also pointed out, the existence of very high-energy cosmic rays can by no means be regarded as an evidence against LSV (Gonzalez-Mestres, 1997d and 1997e). The above non-locality may actually be an approximation to an underlying dynamics involving superluminal particles (Gonzalez-Mestres, 1996, 1997b, 1997f and 1997g), just as electromagnetism looks nonlocal in the potential approximation to lattice dynamics in solid-state physics: it would then correspond to the limit $c\ c_i^{-1} \ \rightarrow \ 0$ where c_i is the superluminal critical speed. Contrary to the $TH\epsilon\mu$-type scenario considered by Coleman and Glashow, where LSV occurs explicitly in the lagrangian already at $k \ = \ 0$, our DLS approach can preserve standard gravitation and general relativity as low-energy limits. Gravitation can naturally be associated to fluctuations of the classical parameters (e.g. the parameters of a differential or nonlocal equation on classical fields) governing dynamics at the fundamental-length scale (Gonzalez-Mestres, 1997a). This would be impossible with the $TH\epsilon\mu$ approach used in (Coleman, & Glashow, 1997). More recent (1998) papers by these authors bring no new result as compared to our 1997 papers and present the same fundamental limitation as their 1997 article.

Are c and α universal? This may be the case for all "elementary" particles, i.e. quarks, leptons, gauge bosons..., but the situation is less obvious for hadrons, nuclei and heavier objects. From a naive soliton model (Gonzalez-Mestres, 1997b and 1997f), we inferred that: a) c is expected to be universal up to very small corrections ($\sim \ 10^{-40}$) escaping all existing bounds; b) an approximate rule can be to take α universal for leptons, gauge bosons and light hadrons (pions, nucleons...) and assume a $\alpha \ \propto \ m^{-2}$ law for nuclei and heavier objects, the nucleon mass setting the scale. With this rule, DRK introduces no anomaly in the relation between inertial and gravitational masses at large scale (Gonzalez-Mestres, 1998c).

3 Ultra-High Energy Cosmic-Ray Physics

If Lorentz symmetry is broken at Planck scale or at some other fundamental length scale, the effects of LSV may be accessible to experiments well below this energy: in particular, they can produce detectable phenomena at the highest observed cosmic ray energies. This is, in particular, due to DRK (Gonzalez-Mestres 1997a, 1997b, 1997c 1997h and 1998a): at energies above $E_{trans} \ \approx \ \pi^{-1/2} \ h^{1/2} \ (2 \ \alpha)^{-1/4} \ a^{-1/2} \ m^{1/2} \ c^{3/2}$, the very small deformation $\Delta \ E$ dominates over the mass term $m^2 \ c^3 \ (2 \ p)^{-1}$ in (3) and modifies all kinematical balances. Because of the negative value of $\Delta \ E$, it costs more and more energy, as energy increases above E_{trans}, to split the incoming logitudinal momentum. With such a LSV pattern, the parton model (in any version), as well as standard formulae for Lorentz contraction and time dilation, are also expected to fail above this energy (Gonzalez-Mestres, 1997b and 1997f) which corresponds to $E \ \approx \ 10^{20} \ eV$ for m = proton mass and $\alpha \ a^2 \ \approx \ 10^{-72} \ cm^2$ (f.i. $\alpha \ \approx \ 10^{-6}$ and a = Planck length), and to $E \ \approx \ 10^{18} \ eV$ for m = pion mass and $\alpha \ a^2 \ \approx \ 10^{-67} \ cm^2$ (f.i. $\alpha \ \approx \ 0.1$ and a = Planck length). Assuming that the earth moves slowly with respect to the absolute rest frame (the "vacuum rest frame"), these effects lead to observable phenomena in future experiments devoted to the highest-energy cosmic rays:

a) For $\alpha \ a^2 \ > \ 10^{-72} \ cm^2$, assuming universal values of α and c , there is no Greisen-Zatsepin-Kuzmin (GZK) cutoff for the particles under consideration. Due to the new kinematics, interactions with microwave background photons are strongly inhibited or forbidden, and ultra-high energy cosmic rays (e.g. protons) from anywhere in the presently observable Universe can reach the earth (Gonzalez-Mestres, 1997a and 1997c).

b) With the same hypothesis, unstable particles with at least two stable particles in the final states of all their decay channels become stable at very high energy. Above E_{trans}, the lifetimes of all unstable particles (e.g. the π^0 in cascades) become much longer than predicted by relativistic kinematics (Gonzalez-Mestres, 1997a, 1997b and 1997c). Then, for instance, the neutron or even the Δ^{++} can be candidates for the primaries of the highest-energy cosmic ray events. If c and α are not exactly universal, many different scenarios can happen concerning the stability of ultra-high-energy particles (Gonzalez-Mestres, 1997a, 1997b and 1997c).

c) In astrophysical processes at very high energy, similar mechanisms can inhibit radiation under external forces (e.g. synchrotron-like), GZK-like cutoffs, decays, photodisintegration of nuclei, momentum loss trough collisions, production of lower-energy secondaries... potentially contributing to solve all basic problems raised by the highest-energy cosmic rays (Gonzalez-Mestres, 1997e).

d) With the same hypothesis, the allowed final-state phase space of two-body collisions is modified by DRK at very high energy and can lead to a sharp fall of cross-sections for incoming cosmic ray energies above $E_{lim} \ \approx \ (2 \ \pi)^{-2/3} \ (E_T \ a^{-2} \ \alpha^{-1} \ h^2 \ c^2)^{1/3}$, where E_T is the energy of the target. As a consequence, and with the previous figures for Lorentz symmetry violation, above some energy E_{lim} between 10^{22} and 10^{24} eV a cosmic ray will not deposit most of its energy in the atmosphere and can possibly fake an exotic event with much less energy (Gonzalez-Mestres, 1997e). Actually, requiring the absence of GZK cutoff above $\approx 10^{20}$ eV and that cosmic rays with energies below $\approx 3.10^{20}$ eV deposit most of their energy in the atmosphere, leads in the DRK scenario to the constraint: 10^{-72} $cm^2 < \alpha \, a^2 < 10^{-61}$ cm^2 , equivalent to $10^{-20} < \alpha < 10^{-9}$ for $a \approx 10^{-26}$ cm . Remarkably enough, assuming full-strength LSV forces a to be in the range 10^{-36} $cm < a < 10^{-30}$ cm . But a $\approx 10^{-6}$ LSV at Planck scale can still fit the data.

e) Effects a) to d) are obtained using only DRK. If dynamical anomalies are added (failure, at very small distance scales, of the parton model and of the standard Lorentz formulae for length and time...), we can expect much stronger effects in the cascade development profiles of cosmic-ray events (Gonzalez-Mestres, 1997b, 1997f and 1998a). Detailed data analysis in next-generation experiments may therefore uncover spectacular new physics and provide a powerful microscope directly focused on the fundamental length (Planck?) scale.

f) Cosmic superluminal particles would produce atypical events with very small total momentum, isotropic or involving several jets (Gonzalez-Mestres, 1996, 1997b, 1997d, 1997 and 1998b).

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