Lorentz symmetry violation, dark matter and dark energy

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Taking into account the experimental results of the HiRes and AUGER collaborations, the present status of bounds on Lorentz symmetry violation (LSV) patterns is discussed. Although significant constraints will emerge, a wide range of models and values of parameters will still be left open. Cosmological implications of allowed LSV patterns are discussed focusing on the origin of our Universe, the cosmological constant, dark matter and dark energy. Superbradyons (superluminal preons) may be the actual constituents of vacuum and of standard particles, and form equally a cosmological sea leading to new forms of dark matter and dark energy.

1. Patterns of Lorentz symmetry violation

A formulation of Planck-scale Lorentz symmetry violation (LSV) testable in ultra-high energy cosmic-ray (UHECR) experiments was proposed in [1,2]. It involves two basic ingredients: i) the existence of a privileged local reference frame (the vacuum rest frame, VRF) ; ii) an energy-dependent parameter driving LSV and possibly making it observable in the ultra-high energy (UHE) region. Then, standard special relativity can remain a low-energy limit in the VRF, contrary to approaches where the critical speed in vacuum is not the same for all standard particles. A simple LSV pattern of the type proposed in [1,2] is quadratically deformed relativistic kinematics (QDRK), where the effective LSV parameter varies quadratically with energy. In the VRF, we can write:

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

E being the particle energy, h the Planck constant, c the speed of light, k the wave vector, a the fundamental length and $[e \ (k \ a)]^2$ a convex function of $(k\,a)^2$. a can correspond to the Planck scale or to a smaller length scale. Expanding (1) for $k \ a \ \ll \ 1$, we get [2]:

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

where p is the particle momentum, α a positive model-dependent constant and m the mass of the particle. For $p \ \gg \ mc$, one has:

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

Kinematic balances are altered, potentially leading to observable phenomena, above a transition energy E_{trans} where the deformation term $-\ p \ c \ \alpha \ (k \ a)^2/2$ becomes of the same order as the mass term $m^2\,c^3\,(2\,p)^{-1}$. For this comparison to make sense, the existence on an absolute local rest frame is a fundamental requirement, even if the ansatz (1)-(3) can be a limit of many different basic theories.

Assuming exact energy and momentum conservation, two important implications of QDRK for UHE particles were already emphasized in [1] : i) QDRK can lead to a suppression of the Greisen-Zatsepin-Kuzmin (GZK) cutoff [3,4] ; ii) unstable particles live longer at UHE than in standard special relativity, and some of them can even become stable at these energies. For such phenomenological applications, the Earth is assumed to move slowly with respect to the VRF.

Subsequent papers [2,5,6] further discussed these issues and that of the universality of the α parameter. Particles with negative values of α could not be stable at UHE, or even at lower energies. Assuming α to be positive, particles with lower values of α would decay into those with larger α. There would be at least one stable UHE particle, with the highest value of α. A recent paper by Mattingly et al. [7] studies a particular application of this discussion to neutrinos. More obvious possibilities can be considered [2,5,6], taking different families of particles. Spontaneous decays of protons and nuclei by photon emission due to LSV can fake the GZK cutoff [8]. Similarly, spontaneous decays of UHE photons into $e^+ \ e^-$ pairs, or the converse effect, may occur at UHE with a moderate difference in α between electrons and photons [5,8].

The model previously proposed by Kirzhnits and Chechin [9] does not lead to such predictions and is unable to produce the suppression of the GZK cutoff [10]. The situation is similar for standard Doubly Special Relativity (SDSR) patterns [11]. In both cases, the laws of Physics are assumed to be the same in all inertial frames. Thus, a symmetry transformation can turn the UHE particle into a less energetic one, leading to a situation where LSV is weaker. We call Weak Doubly Special Relativity (WDSR) our approach that, instead, assumes the existence of a local privileged VRF where special relativity is a low-energy limit. In this case, the laws of Physics are not exactly identical in all inertial frames. The QDRK discussed here is a particular form of WDSR.

In 1971, Sato and Tati [12] suggested that the GZK be explained by an *ad hoc* suppression of hadron production in UHE collisions related to a cutoff in the Lorentz factor below $\approx 10^{11}$. Pion production would then be precluded above $\approx 10^{19}$ eV. Our proposal does not involve such a hypothesis. UHE protons can release a substantial part of their energy in the form of pions when colliding with a photon, provided the photon energy is larger than both the proton mass term and the LSV deformation term of proton kinematics. In QDRK, contrary to the Sato-Tati scenario, the possibility to suppress the GZK cutoff is linked to the exceptionally low energy of cosmic microwave background (CMB) photons and not to an intrinsic cutoff on UHE hadron production.

From a cosmological point of view, it seems reasonable in WDSR patterns to associate to Planck time, or to a smaller time scale, the arisal of LSV in the structure of the physical vacuum. This time scale can be $\approx \ a \ c^{-1}$, or $\approx \ a \ c_s^{-1}$ if a critical superluminal speed c_s exists as in the superbradyon hypothesis. In all cases, the internal structure of the physical vacuum and the history of the Universe may contain strong remnants of their early, Lorentz violating, formation that are not incorporated in standard particle physics and cosmology. Such remnants can also exist as free particles in the present Universe or have influenced structure formation. Issues such as the cosmological constant, inflation, dark matter and dark energy may crucially depend on the role of this new physics.

2. Superbradyons

Standard preon models [13] assumed that preons feel the same minkowskian space-time as quarks, leptons and gauge bosons, and carry the same kind of charges and quantum numbers. But there is no fundamental reason for this assumption.

Superbradyons [1,8,14] would have a critical speed in vacuum $c_s \ \gg \ c$ possibly corresponding to a superluminal Lorentz invariance (a symmetry of the Lorentz type with c_s instead of c). They may be the ultimate constituents of matter, generate LSV for "ordinary" particles (those with critical speed equal to c) and even obey a new mechanics different from standard quantum mechanics [15,16].

After Planck time, superbradyons and "ordinary" particles may coexist in our Universe. In this case, contrary to tachyons, superbradyons would have positive mass and energy, explicitly violate standard Lorentz invariance and be able to spontaneously emit "Cherenkov" radiation in vacuum in the form of "ordinary" particles. Single superbradyons would in general have very weak direct couplings to the conventional interactions of standard particles. In particular, they would not obey the standard relation between inertial and gravitational mass. Then, the vacuum itself may present a similar behavior leading to important effects. We do not consider here : i) the possible existence of several superbradyonic sectors of matter ; ii) the possible differences between the critical speed of superbradyons in their original dynamics without conventional matter, and the actual superbradyon critical speed in our Universe.

In the VRF, the energy E and momentum p of a free superbradyon with inertial mass m and speed v would be :

$$E \ = \ c \ (p^2 \ + \ m^2 \ c_s^2)^{1/2} \qquad (4)$$

$$p \ = \ m \ v \ (1 \ - \ v^2 \ c_s^{-2})^{-1/2} \qquad (5)$$

and, for $v \ \ll \ c_s$, we get :

$$E \ \simeq \ m \ c_s^2 \ + \ m \ v^2/2 \qquad (6)$$

$$p \ \simeq \ m \ v \qquad (7)$$

The kinetic energy E_{kin} is then $E_{kin} \ \simeq \ m \ v^2/2$, and $E_{kin} \ \gg \ p \ c$ for $v \ \gg \ c$. Superbradyons with $v \ > \ c$ are kinematically allowed to decay by emitting standard particles. As lifetimes for such processes can be very long because of the weak couplings expected, the decays may still exist in the present Universe and play a cosmological role. A superbradyon decay would emit a set of conventional particles with total momentum $p_T \ \ll \ E_T \ c^{-1}$ where E_T is the total energy of the emitted particles. Such an event may fake the decay of a conventional heavy particle or the annihilation of two heavy particles, or contain pairs of heavy particles of all kinds. The situation would be similar if the superbradyon decays into one or several lighter superbradyons plus a set of conventional particles, or if two superbradyons annihilate or interact emitting "ordinary" particles.

Superbradyons can thus provide an unconventional form of dark matter in our Universe, and even produce observable signatures at comparatively low energies. Those with $v \ \simeq \ c$ would form a stable sea, except for annihilations. The possibility that superbradyons be a source of standard UHECR was also considered in [17].

3. Experimental considerations

As emphasized in [2,5,6], a LSV $\approx \ 10^{-6}$ at the Planck scale in QDRK for the highest-energy particles would be enough to suppress the GZK cutoff. Thus, such an approach to LSV is currently being tested by ultra-high energy cosmic-ray (UHECR) experiments. Data and analyses from the AUGER [18] and HiRes [19] collaborations possibly confirm the existence of the GZK cutoff. Significant bounds on LSV scenarios will emerge from these data. However, a large domain of LSV patterns and values of parameters will still remain allowed, even for QDRK models [8,20].

A crucial issue is that of the composition of the UHECR spectrum. The AUGER Collaboration has recently reported [22] a systematic inconsistency of available hadronic interaction models when attempting to simultaneously describe the observations of the X_{max} parameter and the number N_μ of produced muons. Data on X_{max} suggest UHECR masses to lie in the range between proton and iron, while N_μ data hint to heavier nuclei.

If the highest-energy particles are nuclei, the AUGER and HiRes results can still be compatible with a LSV $\approx \ 1$ at the Planck scale ($\alpha \ (a)^2 \ \approx \ a_{Pl}^2$, where a_{Pl} is the Planck length) for quarks and gluons. But even assuming that a significant part of the highest-energy particles are protons, the actual bounds on LSV for quarks and gluons will depend on the internal structure of the proton at UHE. Possible spontaneous decays of UHECR protons and nuclei, but also of photons, must equally be considered [8]. Further explorations will thus be required, including satellite experiments [21].

Other LSV patterns (e.g. LDRK, linearly deformed relativistic kinematics, where the parameter driving LSV varies linearly with energy) were discarded in [1] and [2,5,6], as they lead to too strong effects at low energy if the parameters are chosen to produce observable effects at UHECR energies. Hybrid models with high-energy thresholds can still be considered [21], but will not be dealt with here. Inhibition of synchrotron radiation in LSV patterns was predicted and studied in our 1997-2001 papers for QDRK at UHE [2,5,6], leading also to tests like that presented in [23] for 100 MeV synchrotron radiation from the Crab nebula with the same kind of calculation in a version of LDRK.

The energy balances used here involve energies that are very small as compared to those of the particle interactions considered. Therefore, UHECR experiments can also be viewed as tests of energy and momentum conservation and of the validity of quantum mechanics at UHE [15,16]. These phenomenological aspects deserve further study.

As an alternative to standard dark matter, cosmic superbradyons can potentially provide [15] an explanation to the electron and positron abundances reported by PAMELA [24], ATIC [25], Fermi LAT [26], HESS [27] and PPB-BETS [28]. A cosmological sea of superbradyons would still be decaying through the emission of "Cherenkov" radiation in vacuum or releasing conventional particles for some other reason. Whether or not data on electrons do exhibit a bump between 300 GeV and 600 GeV [30] does not change this conclusion. To date, the interpretation of such experimental results in terms of standard dark matter remains unclear [31]. More conventional astrophysical interpretations of these data have been considered in [26,32].

The possible experimental consequences of a superbradyon era in the early Universe deserve further investigation [15,16], as well as the role of superbradyons in the present vacuum, its connection to dark energy effects and the possibility that superbradyonic matter replaces some of the scalar field condensates of standard physics and cosmology.

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