Superluminal Particles in Cosmic-Ray Physics

L. Gonzalez-Mestres[1,2]

[1]*Laboratoire de Physique Corpusculaire, Collège de France, 75231 Paris Cedex 05, France*
[2]*L.A.P.P., B.P. 110, 74941 Annecy-le-Vieux Cedex, France*

Abstract

Present low-energy bounds on Lorentz symmetry violation do not allow to exclude the possible existence of superluminal particles (*superbradyons*) with critical speed in vacuum $c_i \gg c$ (c = speed of light) whose kinematical properties would be close to those of "ordinary" particles (bradyons) apart from the difference in critical speed. If they exist, superbradyons may be the basic building blocks of vacuum and matter at Planck scale, provide most of the matter in the Universe and be natural dark matter candidates. We present an updated discussion of their theoretical and experimental properties, especially as cosmic ray primaries or sources, as well as problems related to their possible direct detection.

1 The Meaning of Relativity

Lorentz symmetry, viewed as a property of dynamics, implies no reference to absolute properties of space and time (Gonzalez-Mestres, 1995a). In a two-dimensional galilean space-time, the wave equation:

$$\alpha \, \partial^2 \phi / \partial t^2 \; - \; \partial^2 \phi / \partial x^2 = F(\phi) \tag{1}$$

with $\alpha = 1/c_o^2$ and c_o = critical speed, remains unchanged under "Lorentz" transformations leaving invariant the squared interval $ds^2 = dx^2 - c_o^2 dt^2$. Matter made with solutions of equation (1) would feel a relativistic space-time even if the real space-time is galilean and if an absolute rest frame exists in the underlying dynamics beyond the wave equation. The solitons of the sine-Gordon equation are obtained taking in (1):

$$F(\phi) \;\; = \;\; - \; (\omega/c_o)^2 \, sin \, \phi \tag{2}$$

ω being a characteristic frequency of the dynamical system. The two-dimensional universe made of such sine-Gordon solitons would behave like a two-dimensional minkowskian world with the laws of special relativity. The actual structure of space and time can only be found by going to deeper levels of resolution where the equation fails, similar to the way high-energy accelerator experiments explore the inner structure of "elementary" particles (but cosmic rays have the highest attainable energies). In such a scenario, that cannot be ruled out by any present experiment, superluminal sectors of matter can exist and even be its ultimate building blocks. This clearly makes sense, as: a) in a perfectly transparent crystal, at least two critical speeds can be identified, those of light and sound; b) the potential approach to lattice dynamics in solid-sate physics is precisely the form of electromagnetism in the limit $c_s \, c^{-1} \; \to \; 0$, where c_s is the speed of sound and c that of light. Superluminal sectors of matter can be consistently generated (Gonzalez-Mestres, 1995a and 1996) replacing in the Klein-Gordon equation the speed of light by a new critical speed $c_i \gg c$ (the subscript i stands for the i-th superluminal sector). All standard kinematical concepts and formulas remain correct, leading to particles with positive mass and energy (**superbradyons**) which are not tachyons. The energy E and momentum p of a superbradyon with mass m and critical speed c_i will be given by the generalized relativistic equations:

$$p \; = \; m \, v \, (1 \; - \; v^2 c_i^{-2})^{-1/2} \tag{3}$$
$$E \; = \; m \, c_i^2 \, (1 \; - \; v^2 c_i^{-2})^{-1/2} \tag{4}$$
$$E_{rest} \; = \; m \, c_i^2 \tag{5}$$

where v is the speed and E_{rest} the rest energy. Each superluminal sector will have its own Lorentz invariance with c_i defining the metric, and is expected to generate a sectorial "gravity". We call the sector made of particles with critical speed in vacuum = c the "ordinary" sector (made of "ordinary" particles or "bradyons").

Being able to write formulae (3)-(5) for all sectors simultaneoulsy requires the existence of an "absolute" rest frame, (**the vacuum rest frame**, VRF, perhaps close to that suggested by the study of cosmic microwave background radiation), the only one where this will be possible. Furthermore, interactions between two different sectors will break both Lorentz invariances and deform their kinematics (an example is given in Gonzalez-Mestres, 1997a; for more recent material, see Gonzalez-Mestres, 1998, and references therein).

The dynamical links between different sectors, including between the "ordinary" and the superluminal sectors, are expected to occur at very high energy and very short distances, in relation with new physics generated beyond the relevant fundamental length(s) (Gonzalez-Mestres, 1995b and 1997b). Such an interaction is also relevant to the very early Universe and is expected to considerably modify its scenario. The critical energy scales will naturally be associated to critical temperatures, leading to a "multi-transition" early Universe where matter itself will transform (Gonzalez-Mestres, 1995b and 1997b). But, at low energy, none of these effects will be apparent in standard tests of special relativity. At the fundamental length scale, and taking a simplified two-dimensional illustration, gravitation may even be a composite phenomenon (Gonzalez-Mestres, 1997b), related for instance to fluctuations of the parameters of equations like:

$$A \, d^2/dt^2 \, [\phi \, (n)] \, + \, H \, d/dt \, [\, \phi \, (n+1) \, - \, \phi \, (n-1)] \, - \, \Phi \, [\phi] \, = \, 0 \qquad (6)$$

where we have quantified space to schematically account for the existence of the fundamental length a, ϕ is a wave function, n designs by an integer lattice sites spaced by a distance a, A and H are coeficients and $\Phi \, [\phi]$ is defined by:

$$\Phi \, [\phi] \, = \, K_{fl} \, [2 \, \phi \, (n) \, - \, \phi \, (n-1) \, - \, \phi \, (n+1)] \, + \, \omega_{rest}^2 \, \phi \qquad (7)$$

K_{fl} being a coefficient and $(2\pi)^{-1} \, \omega_{rest}$ a rest frequency. In the continuum limit, the coefficients $A \, = \, g_{00}$, $H \, = \, g_{01} \, = \, g_{10}$ and $-K_{fl} \, = \, g_{11}$ can be regarded as the matrix elements of a space-time bilinear metric with equilibrium values: $A \, = \, 1$, $H \, = \, 0$ and $K_{fl} \, = \, K$. Then, a small local fluctuation:

$$A \, = \, 1 \, + \, \gamma \qquad (8)$$

$$K_{fl} \, = \, K \, (1 \, - \, \gamma) \qquad (9)$$

with $\gamma \, \ll \, 1$ would be equivalent to a small, static gravitational field created by a far away source. With our deformed Lorentz symmetry approach to relativity (see paper HE.1.3.16 of these Proceedings), general relativity would naturally be preserved at low energy.

2 Superluminal Matter

Apart from the difference in critical speed, superbradyons can be rather "normal" objects to which generalized field theories can possibly be applied (Gonzalez-Mestres, 1997a and 1998), the definition of causality and cosmological horizon depending on the critical speeds under consideration.

2.1 Superbradyons in the Universe   If superbradyons are the building blocks of "ordinary" matter, and c is just a composite critical speed like the speed of sound, we expect to find new (superluminal) forms of matter beyond the Planck scale (where "ordinary" particles may cease to exist), as well as a new physics up to much higher energies. At the same time, superbradyons may well be able to propagate in our vacuum at lower energies, just like light can propagate in a transparent crystal. We expect them to emit "Cherenkov radiation" (ordinary particles and other superbradyons with a lower critical speed in vacuum) when they propagate in vacuum at very high speed. Primaries, secondaries and decay products of this radiation may in principle have extremely high energies and reach suitable detectors. Although superbradyons should eventually loss their kinetic energy until they get traveling at a speed lower than light, if superluminal matter is very abundant it can be continuously generating new fast superbradyons from the decay of very heavy ones. Superbradyons may generate alternatives to inflation in a "Big Bang"-like cosmology (Gonzalez-Mestres, 1995b) and provide nowadays most of the matter in the Universe in extended Friedmann models (Gonzalez-Mestres, 1997b)

incorporating several sectors of matter. As a rough example, we assume that a theory of all gravitation-like forces can be built, taking at each point the vacuum rest frame, and generalize Friedmann equations writing for a flat Universe in the present epoch (where pressure can be neglected):

$$R^{-1} d^2 R/dt^2 \approx -4\pi Z_2 Z_1^{-1}/3 + \Lambda/3 \tag{10}$$

$$(R^{-1} dR/dt)^2 \approx 8\pi Z_2 Z_1^{-1}/3 + \Lambda/3 \tag{11}$$

where R is the distance scale, Λ the cosmological constant and, in a simplified scheme:

$$Z_1 = \rho_a + \rho_O + \Sigma_i (\rho_{a,i} + \rho_{O,i}) \tag{12}$$

$$Z_2 = G_a \rho_a^2 + G_O \rho_O^2 + \Sigma_i (G_{a,i} \rho_{a,i}^2 + G_{O,i} \rho_{O,i}^2) \tag{13}$$

where $G_a = G_N$ is Newton's gravitational constant, ρ_a the density of "acoustic" ordinary matter (the "acoustic" band of the bradyon spectrum as composite objects at Planck scale, i.e. the conventional "elementary" particles), ρ_O the density of "optical" ordinary matter (taken to be positive, see Gonzalez-Mestres, 1997b), $\rho_{a,i}$ and $\rho_{O,i}$ the densities of "acoustic" and "optical" matter of the i-th superluminal sectos (again, taking the densities of "optical" particles to be positive, see Gonzalez-Mestres, 1997b), and the G's are effective gravitation-like coupling constants. $Z_2 Z_1^{-1}$ replaces the usual expression $G_N \rho$ in standard Friedmann equations. Z_1 is the total density of "particle matter", where the expression "particle matter" designs all possible excitations of vacuum that we can describe as particles. These expressions can be derived, for instance, by associating standard Friedmann equations (with only one "gravitational" component) to a lagrangian in terms of R and dR/dt, and generalizing the expressions for kinetic and potential energies in the limit where gravitational couplings between different components of Z_1 are small. An interaction between the different "gravitational" components of Z_1 is, even in this case, implicitly generated by the constraint that R and dR/dt are space-time variables common to all the kinds of matter we consider. Since, at the same time, cosmology considers space-time as being generated by matter, this is indeed an effective dynamical interaction between matter from different sectors. The role of vacuum, the ground state of cosmic matter, is crucial in the generation of a single, absolute space-time with a local absolute rest frame.

Accelerator experiments at future machines (LHC, VLHC...) can be a way to search for superluminal particles (Gonzalez-Mestres, 1997a, 1997c and 1998). However, this approach is limited by the attainable energies, luminosities, signatures and background levels. The coupling of ordinary particles to the superluminal sectors is expected to be strongly energy-dependent. Although direct searches at accelerators provide unique chances and must be carried on, they will only cover a small domain of the allowed parameters for superluminal sectors of matter. Cosmic-ray experiments are not limited in energy and naturally provide very low background levels: they therefore allow for a more general and, on dynamical grounds, better adapted exploration of both Lorentz symmetry violation and possible superluminal particles.

It must also be realized that, if the Poincaré relativity principle is violated, a $1\,TeV$ particle cannot be turned into a $10^{20}\,eV$ particle of the same kind by a Lorentz transformation, and collider events cannot be made equivalent to cosmic-ray events. Very-forward experiments at very high-energy accelerators, covering the kinematical domain equivalent (according to special relativity) to very high-energy cosmic-ray events, would, if technically feasible, be an extremely important research domain allowing to directly test Lorentz symmetry in unexplored kinematical regions. This line of research would in principle justify building accelerators (e.g. for $p - p$ collisions) at energies as high as $\approx 400\,TeV$ per beam (equivalent to $\approx 3.10^{20}\,eV$ cosmic proton hiting a proton at rest in the detector). Such an accelerator energy would simultaneously open a new window to direct search for superbradyons. It must be noticed that the highest observed cosmic-ray energies are closer to Planck scale ($\approx 10^{28}\,eV$) than to electroweak scale ($\approx 10^{11}\,eV$): therefore, if Lorentz symmetry is violated, the study of the highest-energy cosmic rays provides a unique microscope directly focused on Planck scale. The search for very rare events due to superluminal particles in AUGER, AMANDA, OWL, AIRWATCH FROM SPACE... can be a crucial ingredient of this unprecedented investigation (Gonzalez-Mestres, 1997d), searching for the ultimate components of matter beyond Lorentz symmetry.

2.2 Experimental Considerations In what follows, we neglect Lorentz symmetry violation for the physical processes governing our experimental set-up and assume that the earth is not moving at relativistic speed with respect to the local vacuum rest frame. With these hypothesis, superbradyon kinematics has been discussed at length in (Gonzalez-Mestres, 1997a and 1998). Attention must be paid, for instance, to timing signatures: a superbradyon moving with velocity $\vec{v}_i$ with respect to the VRF, and emitted by an astrophysical object, can reach an observer moving with laboratory speed $\vec{V}$ in the VRF at a time, as measured by the observer, previous to the emission time. This remarkable astronomical phenomenon will happen if $\vec{v}_i.\vec{V} > c^2$, and the emitted particle will be seen to evolve backward in time (but it evolves forward in time in the VRF, so that again the reversal of the time arrow is not really a physical phenomenon). Our study also points out that, for $V \ll c$ and $\vec{v}_i.\vec{V} \gg c^2$, the speed $\vec{v}_i'$ of the superbradyon as seen by the observer tends to the limit $\vec{v}_i^{\infty}$, where:

$$\vec{v}_i^{\infty}(\vec{v}_i) = -\vec{v}_i c^2 (\vec{v}_i.\vec{V})^{-1} \tag{14}$$

which sets a universal high-energy limit, independent of c_i, to the speed of superluminal particles as measured by ordinary matter in an inertial rest frame other than the VRF. This limit is not isotropic, and depends on the angle between the speeds $\vec{v}_i$ and $\vec{V}$. A typical order of magnitude for $\vec{v}_i^{\infty}$ on earth is $\vec{v}_i^{\infty} \approx 10^3 c$ if the VRF is close to that suggested by cosmic background radiation. Furthermore, for a very high-speed superluminal cosmic ray with critical speed $c_i \gg c$, it turns out (Gonzalez-Mestres, 1997a and 1998) that the momentum, as measured in the laboratory, does not provide directional information on the source, but on the VRF. Velocity provides directional information on the source, but can be measured only if the particle interacts several times with the detector, or if photons or neutrinos are emitted simultaneously.

Annihilation of pairs of cosmic superluminal particles into ordinary or superluminal ones can release very large kinetic energies. Decays of superbradyons may play a similar role, as well as collisions (especially, inelastic with very large energy transfer) of high-energy superluminal particles with extra-terrestrial ordinary matter. Superluminal particles moving at $v_i > c$ can release anywhere the above mentioned "Cherenkov" radiation in vacuum, providing a new source of (superluminal or ordinary) high-energy cosmic rays. High-energy superbradyons can directly reach the earth. Their interactions have been discussed in (Gonzalez-Mestres, 1996, 1997a, 1997d and 1998). Signatures of very high-energy superluminal particles seem strong enough to escape all backgrounds. Superluminal sources escape quite generally (Gonzalez-Mestres, 1996 and 1998) the Greisen-Zatsepin-Kuzmin cutoff (Greisen, 1966; Zatsepin and Kuzmin, 1966).

References

Gonzalez-Mestres, L., 1995a, Proceedings of the Moriond Workshop on "Dark Matter in Cosmology, Clocks and Tests of Fundamental Laws", Villars January 1995 , Ed. Frontières, p. 645.

Gonzalez-Mestres, L., 1995b, Proceedings of the IV International Workshop on Theoretical and Phenomenological Aspects of Underground Physics (TAUP95), Toledo September 1995, Ed. Nuclear Physics Proceedings, p. 131.

Gonzalez-Mestres, L., 1996, contribution to the 28th International Conference on High Energy Physics (ICHEP 96), Warsaw July 1996, paper hep-ph/9610474 of LANL (Los Alamos) electronic archive.

Gonzalez-Mestres, L., 1997a, papers physics/9702026 and physics/9703020 of LANL archive.

Gonzalez-Mestres, L., 1997b, paper physics/9704017 of LANL archive.

Gonzalez-Mestres, L., 1997c, contribution to the Europhysics International Conference on High-Energy Physics (HEP 97), Jerusalem August 1997, paper physics/9708028.

Gonzalez-Mestres, L., 1997d, Proc. 25th ICRC (Durban, 1997), Vol. 6, p. 109.

Gonzalez-Mestres, L., 1998, Proc. "Workshop on Observing Giant Cosmic Ray Air Showers From $> 10^{20}$ Particles From Space", College Park, November 1997, AIP Conference Proceedings 433, p. 418.

Greisen, K., 1966, Phys. Rev. Lett. 16, 748.

Zatsepin, G.T., & Kuzmin, V.A., 1966, Pisma Zh. Eksp. Teor. Fiz. 4, 114.