PROPERTIES OF
A POSSIBLE CLASS OF PARTICLES
ABLE TO TRAVEL
FASTER THAN LIGHT

L. GONZALEZ-MESTRES

Laboratoire d’Annecy-le-Vieux de Physique des Particules,
B.P. 110 , 74941 Annecy-le-Vieux Cedex, France
and
Laboratoire de Physique Corpusculaire, Collège de France,
11 pl. Marcellin-Berthelot, 75231 Paris Cedex 05 , France

Abstract

The apparent Lorentz invariance of the laws of physics does not imply that space-time is indeed minkowskian. Matter made of solutions of Lorentz-invariant equations would feel a relativistic space-time even if the actual space-time had a quite different geometry (i.e. a galilean space-time). A typical example is provided by sine-Gordon solitons in a galilean world. A ”sub-world” restricted to such solitons would be ”relativistic”, with the critical speed of solitons playing the role of the speed of light. Only the study of the deep structure of matter will unravel the actual geometry of space and time, which we expect to be scale-dependent and determined by the properties of matter itself.

If Lorentz invariance is a property of equations describing a sector of matter at a given scale, an absolute frame (the ”vacuum rest frame”) may exist without contradicting the minkowskian structure of the space-time felt by ordinary particles. But \( c \), the speed of light, will not necessarily be the only critical speed in vacuum: for instance, a superluminal sector of matter may exist related to new degrees of freedom not yet discovered experimentally. Such particles would not be tachyons: they may feel a different minkowskian space-time with a critical speed \( c_1 > c \) and behave kinematically like ordinary particles apart from the difference in critical speed. At \( v \) (speed) \( > c \), they are expected to release ”Cherenkov” radiation (ordinary particles) in vacuum. We present a discussion of possible physical (theoretical and experimental) and cosmological implications of such a scenario, assuming that the superluminal sector couples weakly to ordinary matter.
1. RELATIVITY, SPACE-TIME AND MATTER

In textbook special relativity, mikowskian geometry is an intrinsic property of space and time: any material body moves inside a minkowskian space-time governed by Lorentz transformations and relativistic kinematics. The action itself is basically given by the metrics. General relativity includes gravitation and local invariance within this framework, but the “absoluteness” of the previous concepts remains even if matter modifies the local structure of space and time. Gravitation is given a geometric description within the Minkowskian approach: geometry remains the basic principle of the theory and provides the ultimate dynamical concept. Such an approach has widely influenced modern theoretical physics and, especially, recent grand unified theories.

On the other hand, a look to various dynamical systems studied in the last decades would suggest a more flexible view of the relation between matter and space-time. Lorentz invariance can be viewed as a symmetry of the motion equations, in which case no reference to absolute properties of space and time is required and the properties of matter play the main role. In a two-dimensional galilean space-time, the equation:

\[ \alpha \frac{\partial^2 \phi}{\partial t^2} - \frac{\partial^2 \phi}{\partial x^2} = F(\phi) \]  

(1)

with \( \alpha = 1/c_o^2 \) and \( c_o = \) critical speed remains unchanged under ”Lorentz” transformations leaving invariant the square interval:

\[ ds^2 = dx^2 - c_o^2 dt^2 \]  

(2)

so that matter made with solutions of equation (1) would feel a relativistic space-time even if the real space-time is actually galilean and if an absolute rest frame exists in the underlying dynamics beyond the wave equation. A well-known exemple is provided by the solitons of the sine-Gordon equation taking in (1):

\[ F(\phi) = (\omega/c_o^2) \sin \phi \]  

(3)

A two-dimensional universe made of sine-Gordon solitons plunged in a galilean world would behave like a two-dimensional minkowskian world with the laws of special relativity. Information on any absolute rest frame would be lost by the solitons.

1-soliton solutions of the sine-Gordon equation are known to exhibit ”relativistic” particle properties. With \( |v| < c_o \), a soliton of speed \( v \) is described by the expression:

\[ \phi_v(x, t) = 4 \arctan [\exp (\pm \omega c_o^{-1} (x - vt) (1 - v^2/c_o^2)^{-1/2})] \]  

(4)

with the following properties:

- size \( \Delta x = c_o \omega^{-1} (1 - v^2/c_o^2)^{1/2} \)
- proper time \( d\tau = dt (1 - v^2/c_o^2)^{1/2} \)
- energy \( E = E_o (1 - v^2/c_o^2)^{-1/2}, \) \( E_o \) being the energy at rest and \( m = E_o/c_o^2 \) the ”mass” of the soliton
- momentum \( p = mv \left( 1 - \frac{v^2}{c^2} \right)^{-1/2} \)

so that everything looks perfectly "minkowskian" even if the basic equation derives from a galilean world with an absolute rest frame. In such case, the actual structure of space and time can only be found by going beyond the wave equation to deeper levels of resolution, similar to the way high energy accelerator experiments explore the inner structure of "elementary" particles. The answer may then be scale-dependent and matter-dependent.

Free particles move in vacuum, which is known (i.e. from the Weinberg-Glashow-Salam theory) to be a material medium where condensates and other structures can develop. We measure particles with devices made of particles. We are ourselves made of particles, and we are inside the vacuum. All known particles have a critical speed in vacuum equal to the speed of light, \( c \). But a crucial question remains open: is \( c \) the only critical speed in vacuum, are there particles with a critical speed different from that of light? The question clearly makes sense, as in a perfectly transparent crystal it is possible to identify at least two critical speeds: the speed of light and the speed of sound. The present paper is devoted to explore a simple nontrivial scenario, with two critical speeds in vacuum.

2. PARTICLES IN VACUUM

Free particles in vacuum usually satisfy a dalembertian equation, such as the Klein-Gordon equation for scalar particles:

\[
(c^{-2} \partial^2/\partial t^2 - \Delta) \phi + m^2 c^2 (h/2\pi)^{-2} \phi = 0
\]

where the coefficient of the second time derivative sets \( c \), the critical speed (speed of light), and, given \( c \) and the Planck constant \( h \), the coefficient of the linear term in \( \phi \) sets \( m \), the mass of the particle. To build plane wave solutions, we consider the following physical quantities given by differential operators:

\[
E = i (h/2\pi) \partial/\partial t , \quad \vec{p} = -i (h/2\pi) \vec{\nabla}
\]

and with the definitions:

\[
x^\alpha = ct , \quad p^\alpha = E/c , \quad E = (c^2 \vec{p}^2 + m^2 c^4)^{1/2}
\]

the plane wave is given by:

\[
\phi(x,t) = \exp \left[ -(2\pi i/h) (p^\alpha x^\alpha - \vec{p} \cdot \vec{x}) \right]
\]

from which we can build position and speed operators [1]:

\[
\vec{x}_{op} = (ih/2\pi) (\vec{\nabla}_p - (\vec{p}^2 + m^2 c^2)^{-1} \vec{p})
\]

in momentum space, and:

\[
\vec{v} = d\vec{x}_{op}/dt = (2\pi i/h) [H, \vec{x}_{op}] = (c/p_\alpha) \vec{p}
\]

where \( H \) is the hamiltonian and the brackets mean commutation. We then get:
\[ p_o = mc \left( 1 - \frac{v^2}{c^2} \right)^{-1/2} , \quad \vec{p} = m\vec{v} \left( 1 - \frac{v^2}{c^2} \right)^{-1/2} \]

and, at small \( v/c \):

\[ E_{\text{free}} \simeq \frac{1}{2} mv^2 , \quad \vec{p} \simeq m\vec{v} \]

in which limit, taking \( H = \frac{1}{2} mv^2 + V(\vec{x}_{op}) \), we obtain:

\[ \vec{F} = -\vec{\nabla}V = m \frac{d\vec{v}}{dt} \]

which shows that \( m \) is indeed the inertial mass.

A superluminal sector of matter can be consistently generated, with the conservative choice of leaving the Planck constant unchanged, replacing in the above construction the speed of light \( c \) by a new critical speed \( c_1 > c \). All previous concepts and formulas remain correct, leading to particles with positive mass and energy which are not tachyons and have nothing to do with previous proposals in this field [2]. The new particles will have a larger rest energy, \( E_{\text{rest}} = mc_1^2 \), for a given inertial mass. To produce superluminal mass at accelerators may therefore require very large amounts of energy. In the "non-relativistic" limit \( v/c_1 \ll 1 \), kinetic energy and momentum will remain given by the same expressions as before. Energy and momentum conservation will in principle not be spoiled by the existence of several critical speeds in vacuum.

3. A SCENARIO WITH TWO CRITICAL SPEEDS IN VACUUM

Assume a simple and schematic scenario, with two sectors of matter:

- the "ordinary sector", made of "ordinary particles" with a critical speed equal to the speed of light \( c \);

- a superluminal sector, where particles have a critical speed \( c_1 \gg c \).

Several basic questions arise: can the two sectors interact, and how? what would be the conceptual and experimental consequences? can we observe the superluminal sector and detect its particles? what would be the best experimental approach? It is obviously impossible to give general answers independent of the details of the scenario (couplings, symmetries, parameters...), but some properties and potentialities can be pointed out:

- Even if each sector has its own "Lorentz invariance" involving as the basic parameter the critical speed in vacuum of its own particles, interactions between the two sectors will break both Lorentz invariances. Even if the interaction is mediated by scalar fields preserving apparent Lorentz invariance in the lagrangian density (e.g. with a \( |\phi_o(x)|^2 |\phi_1(x)|^2 \) term where the complex scalar field \( \phi_o \) belongs to the ordinary sector and the complex scalar field \( \phi_1 \) to the superluminal one), the Fourier expansion of the scalar fields shows the unavoidable breaking of both Lorentz invariances.

- Even before considering interaction between the two sectors, Lorentz invariance for both sectors simultaneously will at best be explicit only in a single inertial frame (the \textit{vacuum rest frame}). Apart from the trivial case of space rotations, no linear space-time
transformation can simultaneously preserve the invariance of lagrangian densities for both sectors. However, it will be impossible to identify the vacuum rest frame if one of the sectors produces no measurable effect (e.g. if superluminal particles and their influence on the ordinary sector cannot be observed). In our approach, the Michelson-Morley result is not necessarily incompatible with the existence of some "ether" (the vacuum as a material medium) clearly suggested by recent developments in particle physics. Finding some track of a superluminal sector (e.g. through violations of Lorentz invariance in the ordinary sector) may be the only way to experimentally discover the vacuum rest frame.

- If superluminal particles couple to ordinary matter, they will not in general be found traveling at a speed higher than \( c \) (except near the vertex of accelerator experiments). At superluminal speed, such particles are expected to release "Cherenkov" radiation (i.e. ordinary particles, whose emission in vacuum is kinematically allowed in such case) until they will be decelerated to a speed \( v \leq c \). In accelerator experiments, this "Cherenkov" radiation may provide a clean signature to identify produced superluminal particles. Theoretical studies of tachyons rejected [3] the possibility of "Cherenkov" radiation in vacuum because tachyons are not really different from ordinary particles (they sit in a different kinematical branch, but are the same kind of matter). However, in our case we are dealing with a different kind of matter but superluminal particles will always be in the region of \( E \) and \( \mathbf{p} \) real, with \( E = (c_1 \mathbf{p}^2 + m^2 c_1^2)^{1/2} > 0 \) and can emit "Cherenkov" radiation.

- Gravitation is usually a gauge interaction, related to invariance under local linear transformations of space-time and mediated by a massles ordinary particle (the graviton) which is expected to travel at \( v = c \). Since the graviton belongs to the ordinary sector, it is not expected to play a universal role in the presence of a superluminal sector. As each sector has its own Lorentz invariance, the superluminal sector may generate its own "gravity" with a new "graviton" traveling at critical speed \( c_1 \) and a new "Newton constant". "Gravitational" interactions between the two sectors (including "graviton" mixing) can be generated through the above considered pair of complex scalar fields, but this will lead to anomalies in "gravitational" forces for both sectors. "Gravitational" coupling between ordinary and superluminal particles is in this context expected to be weak. Concepts so far considered as very fundamental (i.e. the universality of the exact equivalence between inertial and gravitational mass) will now fail and leave us with only approximate sectorial properties, even if the real situation may be very difficult to unravel experimentally.

- Stability under radiative corrections (e.g. of the existence of well-defined "ordinary" and "superluminal" sectors) is not always ensured. As the critical speed is related to particle properties in the region of very high energy and momentum, the ultraviolet behaviour of the renormalized theory (e.g. renormalized propagators) will be crucial. However, work on supersymmetry, supergravity and other theories suggests that technical solutions can be found to preserve the identity of each sector as well as the stability of the scheme.

- Superluminal particles may have played a cosmological role leading to substantial changes in the "Big Bang" theory and to a reformulation of the problem of the cosmological constant. Their annihilation into ordinary particles may have generated expansion phenomena similar to inflation, allowing to better describe the formation of large scale structure. Relic superluminal particles may exist, and even dominate the Universe.
4. SOME PRACTICAL CONSIDERATIONS

Searching for effects indicating the possible existence of a superluminal sector appears to be a difficult task. We present here some preliminary remarks:

- At accelerators, hadrons may be the best probe to produce and observe superluminal particles as quarks are coupled to all known interactions. Machines such as LHC have thus interesting potentialities in the field, whereas $e^+e^-$ collisions should be preferred only if superluminal particles couple to the electroweak sector. In an accelerator experiment, a pair of superluminal particles would be produced at $E$ (available energy) = $2mc_1^2$ and Cherenkov effect in vacuum will start only slightly above, at $E = 2mc_1^2 + mc^2 = 2mc_1^2(1 + 1/2 c_1^2/c_2^2) \approx 2mc_1^2$. The Cherenkov cones will quickly become broad, leading to ”almost $4\pi$" events in the rest frame of the superluminal pair.

- Effects of the superluminal sector on the ordinary one may be basically high energy and short distance phenomena, far from conventional tests of Lorentz invariance. Thus, nuclear and particle physics experiments may open new windows. Apart from accelerator experiments, the search for abnormal effects in low energy nuclear physics or in neutrino physics (with neutrinos moving close to speed of light with respect to the vacuum rest frame) deserves serious consideration.

- The present density of superluminal particles, as well as their gravitational properties, are fundamental and unknown parameters in our scenario. Such particles may be part of the dark matter and, if there is a large amount of superluminal matter in the Universe, direct detection may be possible in underground laboratories as well as through pair annihilation in ”astro-particle” experiments.

- Although it seems normal to assume that the superluminal sector is protected by a quantum number and that, at least, the ”lightest superluminal particle” will be stable, this is not unavoidable and we may be inside a sea of very long-lived superluminal particles which decay into ordinary particles. Such decays may then be observable and even play a cosmological role.

- Finally, it should be noticed that we have kept the value of the Planck constant unchanged when building the superluminal sector. This is not really an arbitrary choice, as conservation and quantization of angular momentum make natural our hypothesis if the superluminal and ordinary sector interact. It seems justified to start the search for superluminal particles assuming that their basic quantum properties are not fundamentally different from those of ordinary particles.

References

[1] See, for instance, S.S. Schweber, ”An Introduction to Relativistic Quantum Field Theory”. Row, Peterson and Co. 1961.
[2] See, for instance, ”Tachyons, Monopoles and Related Topics”, Ed. E. Recami. North-Holland 1978.
[3] See, for instance, E. Recami in [2].