PHYSICAL AND COSMOLOGICAL IMPLICATIONS OF A POSSIBLE CLASS OF PARTICLES ABLE TO TRAVEL FASTER THAN LIGHT

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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 (f.i. 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 only an approximate 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, superluminal sectors of matter may exist related to new degrees of freedom not yet discovered experimentally. Such particles would not be tachyons: they may feel different minkowskian space-times with critical speeds much higher than c and behave kinematically like ordinary particles apart from the difference in critical speed. Because of the very high critical speed in vacuum, superluminal particles will have very large rest energies. At speed $v > c$, 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 sectors couple weakly to ordinary matter. The production of superluminal particles may yield clean signatures in experiments at very high energy accelerators. The breaking of Lorentz invariance will be basically a very high energy and very short distance phenomenon, not incompatible with the success of standard tests of relativity. Gravitation will undergo important modifications when extended to the superluminal sectors. The Big Bang scenario, as well as large scale structure, can be strongly influenced by the new particles. If superluminal particles exist, they could provide most of the cosmic (dark) matter and produce very high energy cosmic rays compatible with unexplained discoveries reported in the literature.

1. RELATIVITY, SPACE-TIME AND MATTER

In textbook special relativity, mikowskian geometry is an intrinsic property of space and time: any material body moves with a universal critical speed c (i.e. at speed $v \leq c$), inside a minkowskian space-time governed by Lorentz transformations and relativistic kinematics. The action itself is basically given by a set of metrics. General relativity includes gravitation, 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. This philosophy 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:

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

with $\alpha = 1/c_o^2$ and c_o = critical speed, remains unchanged under "Lorentz" transformations leaving invariant the squared interval:

$$ds^2 = dx^2 - c_o^2 dt^2 \tag{2}$$

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 example is provided by the solitons of the sine-Gordon equation, obtained taking in (1):

$$F(\phi) = (\omega/c_o)^2 \ sin \ \phi \tag{3}$$

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:

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

corresponding to a non-dissipative solution 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 $p = mv\ (1 - v^2/c_o^2)^{-1/2}$

so that everything looks perfectly "minkowskian" even if the basic equation derives from a galilean world with an absolute rest frame. 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 indeed 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 several 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:

$$(c^{-2}\ \partial^2/\partial t^2\ -\ \Delta)\ \phi\ +\ m^2c^2\ (h/2\pi)^{-2}\phi\ =\ 0 \tag{5}$$

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

$$E = i\ (h/2\pi)\ \partial/\partial t \qquad , \qquad \vec{\mathbf{p}} = -i\ (h/2\pi)\ \vec{\nabla}$$

and with the definitions:

$$x^o = ct \qquad , \qquad p^o = E/c \qquad , \qquad E = (c^2\vec{\mathbf{p}}^2\ +\ m^2c^4)^{1/2}$$

the plane wave is given by:

$$\phi(x,t) = exp\ [-(2\pi i/h)\ (p^o x^o - \vec{\mathbf{p}}.\vec{\mathbf{x}})] \tag{6}$$

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

$$\vec{\mathbf{x}}_{op} = (ih/2\pi)\ (\vec{\nabla}_p\ -\ 1/2\ (\vec{\mathbf{p}}^2 + m^2c^2)^{-1}\vec{\mathbf{p}}) \tag{7}$$

in momentum space, and:

$$\vec{\mathbf{v}} = d\vec{\mathbf{x}}_{op}/dt = (2\pi i/h)\ [H, \vec{\mathbf{x}}_{op}] = (c/p_o)\ \vec{\mathbf{p}} \tag{8}$$

where H is the hamiltonian and the brackets mean commutation. We then get:

$$p_o = mc\ (1\ -\ v^2/c^2)^{-1/2} \qquad , \qquad \vec{\mathbf{p}} = m\vec{\mathbf{v}}\ (1\ -\ v^2/c^2)^{-1/2}$$

and, at small v/c :

$$E_{free} \simeq 1/2\ mv^2 \qquad , \qquad \vec{\mathbf{p}} \simeq m\vec{\mathbf{v}} \qquad , \qquad \vec{\mathbf{x}}_{op}\ \simeq\ i\ (h/2\pi)\ \vec{\nabla}_p$$

in which limit, taking $H = 1/2\ mv^2\ +\ V(\vec{\mathbf{x}}_{op})$, we can commute H et $\vec{\mathbf{v}}$ and obtain:

$$\vec{\mathbf{F}} = -\vec{\nabla} V = m\ d\vec{\mathbf{v}}/dt$$

which shows that m is indeed the inertial mass.

Superluminal sectors 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 $c_i > c$ (the subscript i stands for the i-th superluminal sector). 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]. For inertial mass m and critical speed c_i , the new particles will have rest energies:

$$E_{rest} = mc_i^2 \tag{9}$$

To produce superluminal mass at accelerators may therefore require very large energies. In the "non-relativistic" limit $v/c_i \ll 1$, kinetic energy and momentum will remain given by the same non-relativistic expressions as before. Energy and momentum conservation will in principle not be spoiled by the existence of several critical speeds in vacuum: conservation laws will as usual hold for phenomena leaving the vacuum unchanged.

3. A SCENARIO WITH SEVERAL CRITICAL SPEEDS IN VACUUM

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

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

- one or more superluminal sectors, where particles have critical speeds $c_i \gg c$ in vacuum, and each sector is assumed to have its own Lorentz invariance with c_i defining the metric.

Several basic questions arise: can different sectors interact, and how? what would be the conceptual and experimental consequences? can we observe the superluminal sectors and detect their 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.

3a. Lorentz invariance(s)

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 two different sectors will break both Lorentz invariances. With an interaction mediated by complex scalar fields preserving apparent Lorentz invariance in the lagrangian density (e.g. with a $|\phi_o(x)|^2|\phi_1(x)|^2$ term where ϕ_o belongs to the ordinary sector and ϕ_1 to a superluminal one), the Fourier expansion of the scalar fields shows the unavoidable breaking of Lorentz invariances. The concept of mass, as a relativistic invariant, becomes equally approximate and sectorial.

Even before considering interaction between different sectors, Lorentz invariance for all sectors simultaneously will at best be explicit in a single inertial frame (the *vacuum rest frame*, i.e. the "absolute" rest frame). Then, apart from space rotations, no linear space-time transformation can simultaneously preserve the invariance of lagrangian densities for two different sectors. However, it will be impossible to identify the vacuum rest frame if only one sector produces measurable effects (i.e. if superluminal particles and their influence on the ordinary sector cannot be observed). In our approach, the Michelson-Morley result is not incompatible with the existence of some "ether" as suggested by recent results in particle physics: if the vacuum is a material medium where fields and order parameters can condense, it may well have a local rest frame. If superluminal particles couple weakly to ordinary matter, their effect on the ordinary sector will occur at very high energy and short distance, far from the domain of successful conventional tests of Lorentz invariance. Nuclear and particle physics experiments may open new windows in this field. 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.

3b. Space, time and supersymmetry

If the standard minkowskian space-time is not a compulsory framework, we can conceive fundamentally different descriptions of space and time. Just to give examples, we can consider three particular scenarios:

Galilean case. There is no absolute critical speed for particles in vacuum, and space-time transforms according to galilean transformations. The sectorial critical speeds are then the analog of the critical speed of the solitons in the above-mentioned sine-Gordon system sitting in a galilean world.

Minkowskian case. There is an absolute critical speed C in vacuum, with $C \gg c$ and $C \gg c_i$, generated from a cosmic Lorentz invariance not yet found experimentally. As long as physics happens at speed scales much lower than C , the situation is analog to the galilean case. Particles with critical speed equal to C will most likely be weakly coupled to particles from the ordinary and superluminal sectors and be produced only at very high energy. However, massless particles of this type may play a role in low energy phenomena (e.g. a cosmic gravitational interaction). We would reasonably expect particles from the sector with critical speed C (the "cosmic" sector) to be the actual constituents of matter.

Spinorial case. Since spin-1/2 particles exist in nature, and they do not form representations of the rotation group $SO(3)$ but rather of its covering group $SU(2)$, it seems reasonable to attempt a spinorial description of space-time. Lorentz invariance is not required for that purpose, as the basic problem already exists in non-relativistic quantum mechanics. A simple way to relate space and time to a spinor C^2 complex two-dimensional space would be, for a spinor ξ with complex coordinates ξ_1 and ξ_2 , to identify time with the spinor modulus. At first sight, this has the drawback of positive-definiteness, but it naturally sets an arrow of time as well as an origin of the Universe. Then, $t = |\xi|$ could be a cosmic time for an expanding Universe where space would be parameterized by $SU(2)$ transformations and, locally, by its generators which form a vector representation of $SU(2)$ (the tangent space to the S^3 hypersphere in C^2 made topologically equivalent to R^4). The $SU(2)$ invariant metrics $|d\xi|^2 = |d\xi_1|^2 + |d\xi_2|^2$ sets a natural relation between local space and time units. However, the relevant speed scale does not a priori correspond to any critical speed for particles in vacuum. Furthermore, the physically relevant local space and time scales will be determined only by the dynamical properties of vacuum. Radial straight lines in the R^4 space, starting from the point $\xi = 0$, may naturally define the vacuum rest frame at cosmic scale. Any real fonction defined on the complex manifold C^2 will be a fonction of ξ and ξ^* . Spin-1/2 fields will correspond to linear terms in the components of ξ and ξ^* .

Independently of the critical speed, spin-1/2 particles in the vacuum rest frame can have a well-defined helicity:

$$(\vec{\sigma}.\vec{\mathbf{p}}) \ \mid \psi > = \ \pm p \ \mid \psi > \tag{10}$$

which, for free massless particles with critical speed c_i , leads to the Weyl equation:

$$(\vec{\sigma}.\vec{\mathbf{p}}) \ \mid \psi > = \ \pm \ (E/c_i) \ \mid \psi > \tag{11}$$

remaining invariant under sectorial Lorentz transformations with critical speed c_i . When the $SU(2)$ group acting on spinors is dynamically extended to a sectorial Lorentz group, massless helicity eigenstates form irreducible representations of the sectorial Lorentz Lie algebra which, when complexified, can be split into "left" and "right" components. While the original $SU(2)$ symmetry can be a fundamental property of space and time, the Lorentz group and its chiral components are not fundamental symmetries.

In the spinorial space-time, we may attempt to relate the $N = 1$ supersymmetry generators to the spinorial momenta $\partial/\partial\xi_\alpha$ ($\alpha = 1 , 2$) and to their hermitic conjugates. Extended supersymmetry could similarly be linked to a set of spinorial coordinates ξ_α^j ($j = 1 ,..., N$; $\alpha = 1 , 2$) and to their hermitic conjugates, the index j being the internal symmetry index. Contrary to ordinary superspace [4], the new spinorial coordinates would not be independent from space-time coordinates. Time can be the modulus of the $SU(2) \otimes SO(N)$ spinor, taking: $t^2 = \Sigma_{j=1}^N \Sigma_{\alpha=1}^2 \mid \xi_\alpha^j \mid^2$, and as before the three space coordinates would correspond to the directions in the $SU(2)$ tangent space. Then, the ξ_α^j would be "absolute" cosmic spinorial coordinates. For each sector with critical speed c_i , an approximate sectorial supersymmetry can be dynamically generated, involving "left" and "right" chiral spaces and compatible with the sectorial Lorentz invariance.

These examples suggest that, in abandoning the absoluteness of Lorentz invariance, we do not necessarily get a poorer theory. New interesting possibilities appear in the domain of fundamental symmetries as a counterpart to the abandon of a universal Lorentz group.

3c. Gravitation

Mass mixing between particles from different dynamical sectors may occur. Although we expect such phenomena to be weak, they could be more significant for very light particles. Because of mixing between different sectors, mass ceases to be a Lorentz-invariant parameter.

Gravitation is a gauge interaction related to invariance under local linear transformations of space-time. The graviton is a massless ordinary particle, propagating at $v = c$ and associated to ordinary Lorentz invariance. Therefore, it is not expected to play a universal role in the presence of superluminal sectors. In a supersymmetric scheme, it will belong to a sectorial supermultiplet of ordinary particles (supergravity).

Gravitational coupling of superluminal particles to ordinary ones is expected to be weak. Assuming that each superluminal sector has its own Lorentz metric $g_{[i]\mu\nu}$ ($[i]$ for the i-th sector), with c_i setting the speed scale, we may expect each sector to generate its own gravity with a coupling constant κ_i and a new sectorial graviton traveling at speed c_i . In a sectorial supersymmetric (supergravity) theory, each sectorial graviton may belong to a superluminal supermultiplet with critical speed c_i . Gravitation would in all cases be a single and universal interaction only in the limit where all c_i tend to c and where a single metric, as well as possibly a single and conserved supersymmetry, can be used.

As an ansatz, we can assume that the static gravitational coupling between two different sectors is lowered by a factor proportional to a positive power of the ratio between the two critical speeds (the smallest speed divided by the largest one). Static gravitational forces between ordinary matter and matter of the i-th superluminal sector would then be proportional to a positive power of c/c_i which can be a very small number. "Gravitational" interactions between two sectors (including "graviton" mixing) can be generated through the above considered pair of complex scalar fields, although this will lead to anomalies in "gravitational" forces for both sectors. In any case, it seems that concepts so far considered as very fundamental (i.e. the universality of the exact equivalence between inertial and gravitational mass) will now become approximate sectorial properties (like the concept of mass itself), even if the real situation may be very difficult to unravel experimentally. Gravitational properties of vacuum are basically unknown in the new scenario.

3d. Other dynamical properties

No basic consideration (apart from Lorentz invariance, which is not a fundamental symmetry in the present approach) seems to prevent "ordinary" interactions other than gravitation from coupling to the new dynamical sectors with their usual strengths. Conversely, ordinary particles can in principle couple to interactions mediated by superluminal objects. In the vacuum rest frame, covariant derivatives can be written down for all particles and gauge bosons independently of their critical speed in vacuum. Field quantization is performed in hamiltonian formalism, which does not require explicit Lorentz invariance, and quantum field theory can use non-relativistic gauges. We do not expect fundamental consistency problems from the lack of Lorentz invariance, which in quantum field theory is more a physical requirement than a real need, but experiment seems to suggest that superluminal particles have very large rest energies or couple very weakly to the ordinary sector.

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. Although it seems normal to assume that the superluminal sector is protected by a quantum number and that 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 and/or into "lighter" (i.e. with lower rest energies) superluminal ones.

Finally, it should be noticed that we have kept the value of the Planck constant unchanged when building the superluminal sectors. This is not really arbitrary, as conservation and quantization of angular momentum make it natural if the superluminal sectors and the ordinary sector interact. Strictly speaking, h does not play any fundamental dynamical role in the discussion of **Section 2** and its use at this stage amounts to setting an overall scale. It seems justified to start the study of superluminal particles assuming that their quantum properties are not different from those of ordinary particles.

3e. Some signatures

If superluminal particles couple to ordinary matter, they will not often be found traveling at a speed $v > c$ (except near very high-energy accelerators where they can be produced, or in specific astrophysical situations). At superluminal speed, they are expected to release "Cherenkov" radiation, i.e. ordinary particles whose emission in vacuum is kinematically allowed or particles of the i-th superluminal sector for $v > c_i$. Thus, superluminal particles will eventually be decelerated to a speed $v \leq c$. The nature and rate of "Cherenkov" radiation in vacuum will depend on the superluminal particle and can be very weak in some cases. 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). In our case, we are dealing with a different kind of matter but superluminal particles will always be in the region of E and $\vec{\mathbf{p}}$ real, $E = (c_i\vec{\mathbf{p}}^2 \ + \ m^2c_i^4)^{1/2} > 0$, and can emit "Cherenkov" radiation.

In accelerator experiments, this "Cherenkov" radiation may provide a clean signature allowing to identify some of the produced superluminal particles (those with the strongest "Cherenkov" effect). Other superluminal particles may couple so weakly to ordinary matter that "Cherenkov" deceleration in vacuum occurs only at large astrophysical distance scales. If this is the case, one may even, for the far future, think of a very high-energy collider as the device to emit modulated and directional superluminal signals.

Hadron colliders (e.g. LHC) are in principle the safest way to possibly produce superluminal particles, as quarks couple to all known interactions. e^+e^- collisions should be preferred only if superluminal particles couple to the electroweak sector. In an accelerator experiment, a pair of superluminal particles with inertial mass m would be produced at E (available energy) $=$ $2mc_i^2$ and Cherenkov effect in vacuum will start slightly above, at $E \ = \ 2mc_i^2 \ + \ mc^2 = 2mc_i^2(1 \ + \ 1/2 \ c^2/c_i^2) \simeq 2mc_i^2$. The Cherenkov cones will quickly become broad, leading to "almost 4π" events in the rest frame of the superluminal pair.

Apart from accelerator experiments, the search for abnormal effects in low energy nuclear physics, electrodynamics and neutrino physics (with neutrinos moving close to speed of light with respect to the vacuum rest frame) deserves consideration. Mixing with superluminal sectors is likely to produce the strongest effects on photons and light neutrinos. In underground and underwater experiments, dark matter superluminal particles (see **Section 4**) can produce electron, nucleon or nucleus recoil but also inelastic events (particularly interesting if there is no conserved quantum number protecting the relevant superluminal sector). High-energy cosmic ray events can yield crucial signatures (see **Section 5**).

4. COSMOLOGICAL IMPLICATIONS

Superluminal particles may have played a cosmological role leading to substantial changes in the "Big Bang" theory and to a reformulation of several fundamental problems (Planck limit, cosmological constant, horizon, inflation, large scale structure, dark matter...). They may be leading the present evolution of the Universe at very large scale.

4a. The Universe

If superluminal sectors exist and Lorentz invariance is only an approximate sectorial property, the Big Bang scenario may become quite different, as: a) Friedmann equations do no longer govern the global evolution of the Universe, which will be influenced by new sectors of matter coupled to new forces and with different couplings to gravitation; b) gravitation itself will be modified, and can even disappear, at distance scales where Lorentz invariance does no longer hold; c) at these scales, conventional extrapolations to a "Big Bang limit" from low energy scales do not make sense; d) because of the degrees of freedom linked to superluminal sectors, the behaviour of vacuum will be different from standard cosmology; e) the speed of light is no longer an upper limit to the speed of matter. If real space and time are not the basic space-time coordinates (e.g. if space-time is actually described by the above proposed spinorial coordinates transforming under a $SU(2)$ group), the usual Big Bang framework may become unadapted below certain space and time scales, even if a $t = 0$ limit exists. In the above spinorial space-time, naturally providing an expanding Universe, the Big Bang limit can be identified to the point $\xi = 0$. The mathematical relation between the physical, local time scale and the cosmic time $t = \mid \xi \mid$ would depend on dynamics.

Each sectorial Lorentz invariance is expected to break down below a critical distance scale, when the Lorentz-invariant equations (and Lorentz-covariant degrees of freedom) cannot be used and a new dynamics appears. For a sector with critical speed c_i and apparent Lorentz invariance at distance scales larger than k_i^{-1} , where k_i is a critical wave vector scale, we can expect the appearance of a critical temperature T_i given approximately by:

$$k \, T_i \; \approx \; \hbar \, c_i \, k_i \tag{12}$$

where k is the Boltzmann constant and $\hbar$ the Planck constant. Above T_i , the vacuum will not necessarily allow for the previously mentioned particles of the i-th sector and new forms of matter can appear. If k_0 stands for the critical wave vector scale of the ordinary sector, above $T_0 \approx k^{-1} \hbar c k_0$ the Universe may have contained only superluminal particles whereas superluminal and ordinary particles coexist below T_0 . It may happen that some ordinary particles exist above T_0 , but with different properties (like sound above the melting point).

If Lorentz invariance is not an absolute property of space-time, ordinary particles did most likely not govern the beginning of the Big Bang (assuming such a limit exists) and dynamical correlations have been able to propagate must faster than light in the very early Universe. The existence of superluminal particles, and of the vacuum degrees of freedom which generate such excitations, seems potentially able to invalidate arguments leading to the so-called "horizon problem" and "monopole problem", because: a) above T_0 , particles and dynamical correlations are expected to propagate mainly at superluminal speed, invalidating conventional estimates of the "horizon size"; b) below T_0 , annihilation and decays of superluminal particles into ordinary ones will release very large amounts of kinetic energy from the rest masses ($E = mc_i^2$, $c_i \gg c$) and generate a fast expansion of the Universe. Conventional inflationary models rely on Friedmann equations and will not hold in the new scenario. New inflationary models can be considered, but their need is far from obvious. If a "Big Bang" limit exists, and if a generalized form of Friedmann equations can be written down incorporating all sectors and forces, a definition of the horizon distance would be:

$$d_H(t) \; = \; R(t) \int_0^t \; C(t')R(t')^{-1} \; dt' \qquad (13)$$

where d_H is the generalized horizon distance, $R(t)$ is the time-dependent cosmic scale factor and C is the maximum of all critical speeds. This definition is realistic even for ordinary particles, which can be radiated by superluminal ones or produced by their annihilation. C can be infinite if one of the sectors has no critical speed (as in the usual galilean space-time), or if an infinite number of superluminal sectors exist. The homogeneity and isotropy of the present Universe, as manifested through COBE results, are now natural properties.

4b. Particles in the Universe

The coupling between the ordinary sector and the superluminal ones will influence black hole dynamics. A detectable flux of magnetic monopoles (which can be superluminal) is not excluded, as the "horizon problem" can be eliminated without the standard inflationary scheme. Long range correlations introduced by superluminal degrees of freedom can play a role in the formation of objects (i.e. strings) leading to large scale structure of the Universe.

Physics at grand unified scales can present new interesting features. Grand unified symmetries are possible as sectorial symmetries of the vacuum degrees of freedom, even if ordinary particles do not exist above T_0 . But analytic extrapolations (e.g. of running coupling constants) cannot be performed above the phase transition temperature. If kT_0 is not higher than $\approx 10^{14}\ GeV$ ($k_0^{-1} \approx 10^{-27}\ cm$, time scale $\approx 10^{-38}\ s$), the formation of a symmetry-breaking condensate in vacuum may have occurred above T_0 and remain below the transition temperature. Because of superluminal degrees of freedom and of phase transitions at T_0 and at all T_i , it seems impossible to set a "natural time scale" based on extrapolations from the low energy sector (e.g. at the Planck time $t_p \approx 10^{-44}\ s$ from Newton's constant). Arguments leading to the "flatness" or "naturalness" problem, as well as the concept of the cosmological constant and the relation between critical density and Hubble's "constant" (one of the basic arguments for ordinary dark matter at cosmic scale), should be reconsidered.

At lower temperatures, superluminal particles do not disappear. In spite of obvious limitations coming from annihilation, possible decays, decoupling and "Cherenkov radiation" (although such phenomena have by themselves cosmological implications), they can produce important effects in the evolution of the Universe. Superluminal matter may presently be dark, with an unknown coupling to gravitation and coupled to ordinary matter by new, unknown forces. Concentrations of superluminal matter would not necessarily follow the same pattern as "ordinary" galaxies and clusters of galaxies (made of ordinary matter), nor would they need to occur at the same places. Although we expect correlations between the distributions of ordinary and superluminal matter at large scales, it may be difficult (but not impossible, e.g. in the presence of coupled gravitational singularities involving several sectors) to reasonably assume that the gravitational role of galactic halos be due to superluminal particles. Superluminal particles can be very abundant and even provide most of the (dark) matter at cosmic scale, but they will be extremely difficult to detect if they interact very weakly with ordinary matter. Similarly, astrophysical objects made of superluminal matter may elude all conventional observational techniques and be extremely difficult to find.

4c. Possible signatures

If superluminal particles are very abundant, they can, in spite of their expected weak coupling to gravitation, produce some observable gravitational effects. It is not obvious how to identify the superluminal origin of a collective gravitational phenomenon, but clean signatures may exist in some cases (e.g. in gravitational collapses or if it were possible to detect superluminal gravitational waves). If astrophysical concentrations of superluminal matter produce high-energy particles (ordinary or superluminal), cosmic rays may provide a unique way to detect such objects (see **Section 5**). Direct detection of particles from superluminal matter around us in underground and underwater detectors cannot be discarded:

- If m , v and p are the mass, speed and momentum of a relativistic superluminal particle (i.e. at $v \simeq c_i$), and M the mass of an ordinary particle (electron, proton, neutron...) from the target, we expect recoil momenta $p_R \sim p$ and elastic recoil energies $E_R \sim p\ c$. For $m \sim 1\ GeV/c^2$, $v \simeq c_i \sim 10^6\ c$ and $\gamma = (1 - v^2/c_i^2)^{-1/2} \simeq 10^6$, recoil energies $E_R \sim 10^{12}\ GeV$ are obtained similar to the highest-energy cosmic rays observed. Inelastic events can produce much higher energies, comparable to that of the incoming superluminal particle ($\sim 10^{18}\ GeV$ in the previous example).

- Low-energy superluminal particles may also produce detectable events. For instance, at $v \simeq c$ (after "Cherenkov" deceleration in vacuum) or at $v \sim v_e < c$ (v_e being some local escape velocity $\gg 10^{-3}\ c$), a superluminal particle can produce recoil protons and neutrons with energies $\gg 1\ keV$, up to $E_R \sim 1\ GeV$ (for $m \sim 1\ GeV/c^2$ and $v \sim c$). The comparatively high energy of such events can make then detectable and identifiable, even at very small rates, especially in very large volume detectors (e.g. the Cherenkov detectors for neutrino astronomy [5]). Again, inelastic events can yield much higher energy deposition.

- In cryogenic detectors, recoil spectra with average energies $E_R \gg 10^{-6}\ Mc^2$ (M = mass of the target nucleus) can be, according to standard halo models, a signature for particles with escape velocity $v_e \gg 10^{-3}c$ not obeying the usual gravitational laws. Other signatures for particles with escape velocity substantially different from $10^{-3}c$ may come from comparison between results obtained with two different targets (e.g. a hydrogen target and a iodine, xenon or tungsten target). Such particles, whose gravitational behaviour would not fit with conventional halo models, would possibly belong to the superluminal sectors.

5. SUPERLUMINAL PARTICLES AND HIGH-ENERGY COSMIC RAYS

Annihilation of pairs of superluminal particles into ordinary ones can release very large kinetic energies and provide a new source of high-energy cosmic rays. If some superluminal sectors are not protected by a conserved quantum number, their decays may play a similar role. Cosmic rays, especially at high energy and not coming from conventional sources, can therefore be crucial to find a track of superluminal matter.

5a. Ordinary primaries

Annihilation of pairs of slow superluminal particles *into ordinary particles* (and similarly, decays), releasing very high kinetic energies from the superluminal rest energies (the relation $E = mc_i^2$), would yield a unique *cosmic signature* allowing cosmic ray detectors to search for this new kind of matter in the present Universe. *Collisions* (especially, inelastic with very large energy transfer) of high-energy superluminal particles *with extra-terrestrial ordinary matter* may also yield high-energy ordinary cosmic rays. High-energy superluminal particles can be produced from acceleration, decays, explosions... in astrophysical objects made of superluminal matter. Pairs of slow superluminal particles can also annihilate into particles of another superluminal sector with lower c_i , converting most of the rest energies into a large amount of kinetic energy. Superluminal particles moving at $v > c$ can release anywhere "*Cherenkov*" *radiation in vacuum*, i.e. spontaneous emission of particles of a lower critical speed c_i (for $v > c_i$) including ordinary ones, providing a new source of (superluminal or ordinary) high-energy cosmic rays.

5b. Superluminal primaries

High-energy superluminal particles can directly *reach the earth* and undergo collisions inside the atmosphere, producing many secondaries like ordinary cosmic rays. They can also interact with the rock or with water near some underground or underwater detector, coming from the atmosphere or after having crossed the earth, and producing clear signatures. Contrary to neutrinos, whose flux is strongly attenuated by the earth at energies above 10^6 GeV , superluminal particles will in principle not be stopped by earth at these energies. In inelastic collisions, high-energy superluminal primaries can transfer most of their energy to ordinary particles. Even with a very weak interaction probability, and assuming that the superluminal primary does not produce any ionization, the rate for superluminal cosmic ray events can be observable if we are surrounded by important concentrations of superluminal matter. Background rejection would be further enhanced by atypical ionization properties.

5c. Event interpretation

The possibility that superluminal matter exists, and that it plays nowadays an important role in our Universe, should be kept in mind when addressing the two basic questions raised by the analysis of any cosmic ray event: a) the nature and properties of the cosmic ray primary; b) the identification (nature and position) of the source of the cosmic ray.

If the primary is a superluminal particle, it will escape conventional criteria for particle identification and most likely produce a specific signature (e.g. in inelastic collisions) different from those of ordinary primaries (see also **Subsection 4c**). Like neutrino events, in the absence of ionization (which will in any case be very weak) we may expect the event to start anywhere inside the detector. Unlike very high-energy neutrino events, events created by superluminal primaries can originate from a particle having crossed the earth. An incoming, relativistic superluminal particle with momentum p and energy $E_{in} \simeq p\ c_i$, hitting an ordinary particle at rest, can, for instance, release most of its energy into two ordinary particles with momenta close to $p_{max} = 1/2\ p\ c_i\ c^{-1}$ and oriented back to back in such a way that the two momenta almost cancel. Then, an energy $E_R \simeq E_{in}$ would be transferred to ordinary secondaries. At very high energy, such events would be easy to identify in large volume detectors, even at very small rate.

If the source is superluminal, it can be located anywhere (and even be a free particle) and will not necessarily be at the same place as conventional sources of ordinary cosmic rays. High-energy cosmic ray events originating form superluminal sources will provide hints on the location of such sources and be possibly the only way to observe them.

The energy dependence of the events should be taken into account. At very high energies, the Greisen-Zatsepin-Kuzmin cut-off [6] does not in principle hold for cosmic ray events originating from superluminal matter: this is obvious if the primaries are superluminal particles that we expect to interact very weakly with the cosmic microwave background, but is also true for ordinary primaries as we do not expect them to be produced at the locations of ordinary sources and there is no upper bound to their energy around 100 EeV. However, besides "Cherenkov" deceleration, a superluminal cosmic background radiation may exist and generate (at much higher energies?) its own GZK cutoffs for the superluminal sectors.

To date, there is no well established interpretation [5 - 7] of the highest-energy cosmic ray events [8]. Primaries (ordinary or superluminal) originating from superluminal particles are acceptable candidates and can possibly escape several problems (event configuration, source location, energy dependence...) faced by cosmic rays produced at ordinary sources.

Note. Previous papers on the subject are references [9] - [12].

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