Observing Air Showers from Cosmic Superluminal Particles

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Abstract. The Poincaré relativity principle has been tested at low energy with great accuracy, but its extrapolation to very high-energy phenomena is much less well established. Lorentz symmetry can be broken at Planck scale due to the renormalization of gravity or to some deeper structure of matter: we expect such a breaking to be a very high energy and very short distance phenomenon. If textbook special relativity is only an approximate property of the equations describing a sector of matter above some critical distance scale, an absolute local frame (the "vacuum rest frame", VRF) can possibly be found and superluminal sectors of matter may exist related to new degrees of freedom not yet discovered experimentally. The new superluminal particles (**"superbradyons"**, i.e. bradyons with superluminal critical speed) would have positive mass and energy, and behave kinematically like "ordinary" particles (those with critical speed in vacuum equal to c , the speed of light) apart from the difference in critical speed (we expect $c_i \gg c$, where c_i is the critical speed of a superluminal sector). They may be the ultimate building blocks of matter. At speed $v > c$, they are expected to release "Cherenkov" radiation ("ordinary" particles) in vacuum. Superluminal particles could provide most of the cosmic (dark) matter and produce very high-energy cosmic rays. We discuss: a) the possible relevance of superluminal matter to the composition, sources and spectra of high-energy cosmic rays; b) signatures and experiments allowing to possibly explore such effects. Very large volume and unprecedented background rejection ability are crucial requirements for any detector devoted to the search for cosmic superbradyons. Future cosmic-ray experiments using air-shower detectors (especially from space) naturally fulfil both requirements.

"The impossibility to disclose experimentally the absolute motion of the earth seems to be a general law of Nature"

H. Poincaré

"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"

A. Einstein

RELATIVITY, MATTER AND CRITICAL SPEEDS

If Lorentz symmetry is viewed as a dynamical property of the motion equations, no reference to absolute properties of space and time is required [1]. 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):

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

where ω is a characteristic frequency of the dynamical system. 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, as if the Poincaré relativity principle (see [2] to [5] for the genesis and evolution of this deep concept) were indeed a law of Nature, even if actually the basic equation derives from a galilean world with an absolute rest frame (a system built "on top of a table", with $c_o \ll c$). 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 (but cosmic rays have the highest attainable energies).

At this stage, two crucial questions arise: a) is c (the speed of light) the only critical speed in vacuum, are there particles with a critical speed different from that of light? [1,6]; b) can the ultimate building blocks of matter be superluminal? [7,8]. These questions make sense, as: a) in a perfectly transparent crystal it is possible to identify at least two critical speeds, those of light and sound, and light can interact with phonons; b) the potential approach to lattice dynamics in solid-sate physics is precisely the form of electromagnetism in the limit $c_s\ c^{-1} \rightarrow 0$, where c_s is the speed of sound. Superluminal sectors of matter can be consistently generated [1,9], with the conservative choice of leaving the Planck constant unchanged, 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 [10] remain correct, leading to particles with positive mass and energy which are not tachyons. We shall call them **superbradyons** as, according to standard vocabulary [11], they are bradyons with superluminal critical speed in vacuum. The energy E and momentum p of a superluminal particle of mass m and critical speed c_i will be given by the generalized relativistic equations:

$$p \ = \ m \ v \ (1 \ - \ v^2 c_i^{-2})^{-1/2} \tag{4}$$

$$E \ = \ m \ c_i^2 \ (1 \ - \ v^2 c_i^{-2})^{-1/2} \tag{5}$$

$$E_{rest} \ = \ m \ c_i^2 \tag{6}$$

where v is the speed and E_{rest} the rest energy. 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. Each superluminal sector will have its own Lorentz invariance with c_i defining the metric, and is expected to generate a sectorial "gravity". Interactions between two different sectors will break both Lorentz invariances. Lorentz invariance for all sectors simultaneously will at best be explicit (i.e. exhibiting the diagonal sectorial Lorentz metric) in a single inertial frame (**the vacuum rest frame**, VRF, i.e. the "absolute" rest frame). 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 whose identification would be prevented by the sectorial Lorentz symmetries in the low-momentum limit (where different sectors do not mix and the sectorial Lorentz symmetries become exact laws, so that each sector feels a "Poincaré relativity principle").

If superluminal particles couple weakly to ordinary matter, their effect on the ordinary sector will occur at very high energy and short distance [12], far from the domain of successful conventional tests of Lorentz invariance [13,14]. In particular, superbradyons naturally escape the constraints on the critical speed derived in some specific models [15,16] based on the $TH\epsilon\mu$ approach [17] , as their mixing with the ordinary sector is expected to be strongly energy-dependent [8,18]. High-energy experiments can therefore open new windows in this field. Finding some track of a superluminal sector (e.g. through violations of Lorentz invariance in the ordinary sector or by direct detection of a superluminal particle) may be the only way to experimentally discover the VRF. Superluminal particles lead to consistent cosmological models [6,7,9], where they may well provide most of the cosmic (dark) matter [19]. Although recent criticism to this suggestion has been emitted in a specific model on the grounds of gravitation theory [20], the framework used is crucially different from the multi-graviton approach suggested in our papers where we propose (e.g. [1,9]) that each dynamical (ordinary or superluminal) sector generates its own gravitation associated to the sectorial Lorentz symmetry and couplings between different "gravitons" are expected to be weak. Superbradyons can be the ultimate building blocks from which superstrings would be made and a "pre-Big Bang" cosmology would emerge. Nonlocality at Planck scale would then be an approximation to this dynamics in the limit $c \ c_i^{-1} \ \rightarrow \ 0$, where superluminal signals undergo apparent "instantaneous" propagation similar to electromagnetic interactions described by a potential model of lattice dynamics in solid state physics.

IMPLICATIONS FOR HIGH-ENERGY COSMIC RAYS

Accelerator experiments at future machines (LHC, VLHC...) can be a way to search for superluminal particles [12,18]. However, this approach is limited by the attainable energies, luminosities, signatures and low-background levels. Although the investigation at accelerators provides unique chances and must be carried on, it 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. 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.

The highest observed cosmic-ray energies (up to 3.10^{20} eV) 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 [7,8,21]. 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 [12,18,22,23]. In what follows we assume that the earth is not moving at relativistic speed with respect to the local vacuum rest frame.

Superluminal kinematics

The kinematical properties and Lorentz transformations of high-energy superluminal particles have been discussed elsewhere [12]. If an absolute rest frame exists, Lorentz contraction is a real physical phenomenon and is governed by the factor $\gamma_i^{-1} = (1 - v^2 c_i^{-2})^{1/2}$ for the i-th superluminal sector, so that there is no Lorentz singularity when a superluminal particle crosses the speed value $v = c$ in a frame measured by ordinary matter. Similarly, if superbradyons have any coupling to the electromagnetic field (adding in the standard way the electromagnetic four-potential to the superluminal four-momentum to build the covariant derivative in the VRF), we expect the magnetic force to be proportional to $v\ c_i^{-1}$ instead of $v\ c^{-1}$. Contrary to tachyons, superbradyons can emit "Cherenkov" radiation (i.e. particles with lower critical speed) in vacuum. If $c_i \gg 10^3\ c$, and if the VRF is close to that defined requiring isotropy of cosmic microwave background radiation, high-energy superluminal particles will be seen on earth as traveling mainly at speed $v \approx 10^3\ c$, as can be seen from the following analysis. Since we expect to measure the energy of superluminal particles through interactions with detectors made of "ordinary" particles, we can define, in the rest frame of an "ordinary" particle moving at speed $\vec{\mathbf{V}}$ with respect to the VRF, the energy and momentum of a superluminal particle to be the Lorentz-tranformed of its VRF energy and momentum taking c as the critical speed parameter for the Lorentz transformation. Then, the mass of the superluminal particle will depend on the inertial frame. The energy E'_i and momentum $\vec{\mathbf{p}}'_\mathbf{i}$ of the superluminal particle i (belonging to the i-th superluminal sector and with energy E_i and momentum $\vec{\mathbf{p}}_\mathbf{i}$ in the VRF) in the new rest frame, as measured by ordinary matter from energy and momentum conservation (e.g. in decays of superluminal particles into ordinary ones), will be:

$$E'_i \ = \ (E_i \ - \ \vec{\mathbf{V}}.\vec{\mathbf{p}}_\mathbf{i}) \ (1 \ - \ V^2c^{-2})^{-1/2} \tag{7}$$
$$\vec{\mathbf{p}}'_\mathbf{i} \ = \ \vec{\mathbf{p}}'_\mathbf{i,L} \ + \ \vec{\mathbf{p}}'_{\mathbf{i},\perp} \tag{8}$$
$$\vec{\mathbf{p}}'_\mathbf{i,L} \ = \ (\vec{\mathbf{p}}_\mathbf{i,L} \ - \ E_i \ c^{-2} \ \vec{\mathbf{V}}) \ (1 \ - \ V^2c^{-2})^{-1/2} \tag{9}$$
$$\vec{\mathbf{p}}'_{\mathbf{i},\perp} \ = \ \vec{\mathbf{p}}_{\mathbf{i},\perp} \tag{10}$$

where $\vec{\mathbf{p}}_\mathbf{i,L} \ = \ V^{-2} \ (\vec{\mathbf{V}}.\vec{\mathbf{p}}_\mathbf{i}) \ \vec{\mathbf{V}}$, $\vec{\mathbf{p}}_{\mathbf{i},\perp} \ = \ \vec{\mathbf{p}}_\mathbf{i} - \vec{\mathbf{p}}_\mathbf{i,L}$ and similarly for the longitudinal and transverse components of $\vec{\mathbf{p}}'_\mathbf{i}$. We are thus led to consider the effective squared mass:

$$M^2_{i,c} \ = \ c^{-4} \ (E^2_i \ - \ c^2p^2_i) \ = \ m^2_ic^{-4}c^4_i \ + \ c^{-2}(c^{-2}c^2_i \ - \ 1) \ p^2_i \tag{11}$$

which depends on the VRF momentum of the particle. m_i is the invariant mass of particle i , as seen by matter from the i-th superluminal sector (i.e. with critical speed in vacuum = c_i). While "ordinary" transformation laws of energy and momentum are not singular, even for a superluminal particle, the situation is different for the transformation of a superluminal speed, as will be seen below. Furthermore, if the superluminal particle has velocity $\vec{\mathbf{v}}_\mathbf{i} \ = \ \vec{\mathbf{V}}$ in the VRF, so that it is at rest in the new inertial frame, we would naively expect a vanishing momentum, $\vec{\mathbf{p}}'_\mathbf{i} \ = \ \mathbf{0}$. Instead, we get:

$$\vec{\mathbf{p}}'_\mathbf{i} \ = \ - \ \vec{\mathbf{p}}_\mathbf{i} \ (c^{-2}c^2_i \ - \ 1) \ (1 \ - \ V^2c^{-2})^{-1/2} \tag{12}$$

and $p'_i \ \gg \ p_i$, although $p'_ic \ \ll \ E'_i$ if $V \ \ll \ c$. This reflects the non-covariant character of the 4-momentum of particle i under "ordinary" Lorentz transformations. Thus, even if the directional effect is small in realistic situations (f.i. on earth), the decay of a superluminal particle at rest into ordinary particles will not lead to an exactly vanishing total momentum if the inertial frame is different from the VRF.

In the rest frame of an "ordinary" particle moving with speed $\vec{\mathbf{V}}$ with respect to the VRF, we can estimate the speed $\vec{\mathbf{v}}'_\mathbf{i}$ of the previous particle i writing:

$$\vec{\mathbf{v}}_\mathbf{i} \ = \ \vec{\mathbf{v}}_\mathbf{i,L} \ + \ \vec{\mathbf{v}}_{\mathbf{i},\perp} \tag{13}$$

where $\vec{\mathbf{v}}_\mathbf{i,L} \ = \ V^{-2}(\vec{\mathbf{V}}.\vec{\mathbf{v}}_\mathbf{i}) \ \vec{\mathbf{V}}$, and similarly for the longitudinal and transverse components of $\vec{\mathbf{v}}'_\mathbf{i}$. Then, the transformation law is:

$$\vec{\mathbf{v}}'_\mathbf{i,L} \ = \ (\vec{\mathbf{v}}_\mathbf{i,L} \ - \ \vec{\mathbf{V}}) \ (1 \ - \ \vec{\mathbf{v}}_\mathbf{i}.\vec{\mathbf{V}} \ c^{-2})^{-1} \tag{14}$$
$$\vec{\mathbf{v}}'_{\mathbf{i},\perp} \ = \ \vec{\mathbf{v}}_{\mathbf{i},\perp} \ (1 \ - \ V^2c^{-2})^{1/2} \ (1 \ - \ \vec{\mathbf{v}}_\mathbf{i}.\vec{\mathbf{V}} \ c^{-2})^{-1} \tag{15}$$

leading to singularities at $\vec{\mathbf{v}}_\mathbf{i} \ = \ c^2$ which correspond to a change in the arrow of time (due to the distorsion generated by the Lorentz transformation of space-time) as seen by ordinary matter traveling at speed $\vec{\mathbf{V}}$ with respect to the VRF.

Experimental implications

At $v_{i,L} > c^2 V^{-1}$, a superluminal particle moving forward in time in the VRF will appear as moving backward in time to an observer made of ordinary matter and moving at speed $\vec{\mathbf{V}}$ in the same frame. On earth, taking $V \approx 10^{-3}\ c$ (if the VRF is close to that suggested by cosmic background radiation, e.g. [24]), the apparent reversal of the time arrow will occur mainly at $v_i \approx 10^3\ c$. If $c_i \gg 10^3\ c$, phenomena related to propagation backward in time of produced superluminal particles may be observable in future accelerator experiments slightly above the production threshold. In a typical event where a pair of superluminal particles would be produced, we expect in most cases that one of the superluminal particles propagates forward in time and the other one propagates backward. As previously stressed, the infinite velocity (value of v'_i) associated to the point of time reversal does not, according to (7) and (9), correspond to infinite values of energy and momentum. The backward propagation in time, as observed by devices which are not at rest in the VRF, is not really physical (the arrow of time is well defined in the VRF for all physical processes) and does not correspond to any real violation of causality. The apparent reversal of the time arrow for superluminal particles at $\vec{\mathbf{v}}_{\mathbf{i}}.\vec{\mathbf{V}} > c^2$ would be a consequence of the bias of the laboratory time measurement due to our motion with respect to the absolute rest frame. The distribution and properties of such superluminal events, in an accelerator experiment or in a large-volume cosmic-ray detector, would obviously be in correlation with the direction and speed of the laboratory's motion with respect to the VRF. It would provide fundamental cosmological information, complementary to informations on "ordinary" matter provided by measurements of the cosmic microwave background.

From (14) and (15), we also notice that, for $V \ll c$ and $\vec{\mathbf{v}}_{\mathbf{i}}.\vec{\mathbf{V}} \gg c^2$, the speed $\vec{\mathbf{v}}'_{\mathbf{i}}$ tends to the limit $\vec{\mathbf{v}}_{\mathbf{i}}^{\infty}$, where:

$$\vec{\mathbf{v}}_{\mathbf{i}}^{\infty}\ (\vec{\mathbf{v}}_{\mathbf{i}}) \quad = \quad -\ \vec{\mathbf{v}}_{\mathbf{i}}\ c^2\ (\vec{\mathbf{v}}_{\mathbf{i}}.\vec{\mathbf{V}})^{-1} \tag{16}$$

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 $\vec{\mathbf{v}}_{\mathbf{i}}$ and $\vec{\mathbf{V}}$. A typical order of magnitude for $\vec{\mathbf{v}}_{\mathbf{i}}^{\infty}$ on earth is $\vec{\mathbf{v}}_{\mathbf{i}}^{\infty} \approx 10^3\ c$ if the VRF is close to that suggested by cosmic background radiation. If C is the highest critical speed in vacuum, infinite speed and reversal of the arrow of time occur only in frames moving with respect to the VRF at speed $V \geq c^2 C^{-1}$. Finite critical speeds of superluminal sectors, as measured by ordinary matter in frames moving at $V \neq 0$, are anisotropic. Therefore, directional detection of superluminal particles would allow to directly identify the VRF and even to check whether it can be defined consistently, simultaneously for all dynamical sectors. If a universal, local VRF cannot be defined, translational and rotational modes may appear between different kinds of matter generating significant cosmological effects (e.g. a cosmic rotation axis for "ordinary" matter).

A superbradyon moving with velocity $\vec{\mathbf{v}}_\mathbf{i}$ with respect to the VRF, and emitted by an astrophysical object, can reach an observer moving with laboratory speed $\vec{\mathbf{V}}$ in the VRF at a time, as measured by the observer, previous to the emission time. This remarkable astronomical phenomenon will happen if $\vec{\mathbf{v}}_\mathbf{i}.\vec{\mathbf{V}} \ > \ c^2$, 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). If they interact several times with the detector, superbradyons can be a directional probe preceding the detailed observation of astrophysical phenomena, such as explosions releasing simultaneously neutrinos, photons and superluminal particles (although causality is preserved in the VRF). For a high-speed superluminal cosmic ray with critical speed $c_i \ \gg \ c$, 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, which is far from guaranteed, or if the superluminal particle is associated to a collective phenomenon involving several sectors of matter and emitting also photons or neutrinos simultaneously. In the most favourable case, directional detection of high-speed superluminal particles in a very large detector would allow to trigger a dedicated astrophysical observation in the direction of the sky determined by the velocity of the superluminal particle(s). If d is the distance between the observer and the astrophysical object, and Δt the time delay between the detection of the superluminal particle(s) and that of photons and neutrinos, we have: $d \ \simeq \ c \ \Delta t$.

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. Decays of superluminal particles may play a similar role. Collisions (especially, inelastic with very large energy transfer) of high-energy superluminal particles with extraterrestrial ordinary matter may also yield high-energy ordinary cosmic rays. 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 $v_i \ > \ c$ can release anywhere "Cherenkov" radiation in vacuum, i.e. spontaneous emission of particles of a lower critical speed c_j (for $v_i \ > \ c_j$) including ordinary ones, providing a new source of (superluminal or ordinary) high-energy cosmic rays. 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 ionization, the rate for superluminal cosmic ray events can be observable if we are surrounded by important concentrations of superluminal matter, which is possible in suitable cosmologies [7]. Atypical ionization properties would further enhance background rejection, but ionization can be in contradiction with the requirement of very weak coupling to ordinary matter unless the coupling is energy-dependent.

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. Like neutrino events, in the absence of ionization 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 $E_{in} \simeq p_i \, c_i$ in the VRF, hitting an ordinary particle at rest, can, for instance, release most of its energy into two ordinary particles with momenta (in the VRF) close to $p_{max} = 1/2 \; p_i \; c_i \; c^{-1}$ 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. More generally, we can expect several jets in a configuration with very small total momentum as compared to c^{-1} times the total energy, or a basically isotropic event. Corrections due to the earth motion must be applied (see previous Section) before defining the expected event configuration in laboratory or air-shower experiments, but the basic trends just described remain. 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 in the case of "Cherenkov" emission) 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 (GZK) cutoff [25,26] 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 applies also in practice to 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. Besides "Cherenkov" deceleration, a superluminal cosmic background radiation may exist and generate its own GZK cutoffs for the superluminal sectors. However, if there are large amounts of superluminal matter around us, they can be the main superluminal source of cosmic rays reaching the earth. To date, there is no well-established interpretation of the highest-energy cosmic-ray events. 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.

POTENTIALITIES OF AIR-SHOWER DETECTORS

Since the discovery of superluminal matter would be an unprecedented event in the history of Physics, and we do not know at what energy scale it would manifest itself, direct detection of cosmic superluminal particles (CSL) deserves special consideration having in mind the exceptional potentialities of future cosmic-ray detectors. As we expect a very weak coupling between superluminal and "ordinary" matter, except possibly at Planck scale, it is crucial to be able to cover an unusually large target volume. If the coupling increases with energy, it can compensate the possible fall with energy of the CSL flux and make the highest-energy experiments especially adapted to the search for CSL. Future air-shower detectors devoted to the highest-energy cosmic rays will observe the largest target volumes ever reached in a particle physics experiment (especially in the case of satellite-based programs such as OWL or AIRWATCH FROM SPACE). Due to the energies they are able to cover, and considering the possibility that Lorentz symmetry be violated at Planck scale, such experiments are as sensitive to phenomena generated by Planck-scale physics as any possible particle physics experiment can be.

To possibly observe CSL, background rejection must be unprecedentedly powerful. This would be the case for ultra-high energy events generated by CSL. As previously stressed, the ratio $E_{in} \simeq p_i \ c_i$ (in the VRF) provides a unique event profile: since the total momentum of the produced ordinary particles is very small as compared to the total available energy (using c as the conversion factor), the event cannot have the usual, sharply forward-peaked shape of showers produced by "ordinary" cosmic rays. Instead, it can be made of two or more (broad) jets, or be basically isotropic. No "ordinary" ultra-high energy particle can produce such an event shape. The discussion remains valid in any reference frame moving at low speed with respect to the VRF, with the corrections discussed previously. Therefore, air-shower detectors should basically look for events originating at any depth in the atmosphere (like neutrino-induced events) but which, unlike neutrino events where a single elementary particle gets part of the incoming neutrino momentum and subsequently produces a conventional shower profile, do not present a single privileged direction for the produced particles and have instead a tendency to be isotropic. Furthermore, if the earth moves at a speed $\approx 10^{-3} \ c$ with respect to the VRF and $c \ c_i^{-1} \ \ll \ 10^{-3}$, the total momentum of the produced particles must in most events cancel with $\approx 10^{-3}$ precision as compared to the total energy, up to fluctuations due to unobserved neutrals and to measurement uncertainties.

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