HE 1.2.36

ABSENCE OF GREISEN-ZATSEPIN-KUZMIN CUTOFF AND STABILITY OF UNSTABLE PARTICLES AT VERY HIGH ENERGY, AS A CONSEQUENCE OF LORENTZ SYMMETRY VIOLATION

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ABSTRACT

Special relativity has been tested at low energy with great accuracy, but its extrapolation to very high-energy phenomena is much less well established. Introducing a critical distance scale, a , below 10^{-25} cm (the wavelength scale of the highest-energy observed cosmic rays) allows to consider models, compatible with standard tests of special relativity, where a small violation of Lorentz symmetry (a can, for instance, be the Planck length) produces dramatic effects on the properties of high-energy cosmic rays. Not only the Greisen-Zatsepin-Kuzmin (GZK) cutoff on very high-energy protons and nuclei does no longer apply, but particles which are unstable at low energy (neutron, several nuclei, some hadronic resonances like the Δ^{++}...) would become stable at very high energy. The muon would also become stable or very long lived at very high energy if one of the two neutrinos associated to the light charged leptons (electron, muon) has a mass. Similar considerations apply to the τ lepton. We discuss several possible scenarios originating these phenomena, as well as the cosmic ray energy range (well below the energy scale associated to the fundamental length) and experiments where they could be detected. Observable effects are predicted for the highest-energy cosmic rays.

LORENTZ SYMMETRY AS A LOW-ENERGY LIMIT

Low-energy experiments (Lamoreaux, Jacobs, Heckel, Raab and Forston, 1986 ; Hills and Hall, 1990) confirm Lorentz invariance to an impressive accuracy. However, the extrapolation between these results and high-energy phenomena is far from obvious. Figures can change by 34 orders of magnitude between keV and 10^{20} eV scales if Lorentz symmetry violation is proportional to $(k\ a)^2$ where k is the wave vector scale and a a fundamental length. Such a behaviour seems to be characteristic of many models where local Lorentz invariance is broken through non-local phenomena at the fundamental length scale (f.i. the Planck scale). These models lead to a dispersion relation of the form (Gonzalez-Mestres, 1997):

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

where E is the energy of the particle, h the Planck constant, c the speed of light, a a fundamental length scale that we can naturally identify with the Planck length (but other choices of the fundamental distance scale are possible), k the wave vector modulus and $[e\ (k\ a)]^2$ is a convex function of $(k\ a)^2$ obtained from vacuum dynamics. We have checked that this is also a fundamental property of old scenarios breaking local Lorentz invariance (f.i. Rédei, 1967), although such a phenomenon seems not to have been noticed by the authors. For a particle of mass m , an ansatz based on an isotropic, continuous modification of the Bravais lattice dynamics is (Gonzalez-Mestres, 1997):

$$e\,(k\ a) \ = \ [4\ sin^2\ (ka/2) \ + \ (2\pi\ a)^2\ h^{-2}\ m^2\ c^2]^{1/2} \tag{2}$$

whereas we have found that simple extensions of the ansatz by Rédei (1967) lead to expressions like:

$$e\,(k\ a) \ = \ [10 \ + \ 30\ (k\ a)^{-2}\ cos\ (k\ a) \ - \ 30\ (k\ a)^{-3}\ sin\ (k\ a) \ + \ (2\pi\ a)^2\ h^{-2}\ m^2\ c^2]^{1/2} \tag{3}$$

which has similar properties to (2). In both cases, and rather generally, we find that, at wave vector scales below the inverse of the fundamental length scale, Lorentz symmetry violation in relativistic kinematics can be parameterized writing:

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

where α is a positive constant between 10^{-1} and 10^{-2} . At high energy, we can write:

$$e\,(k\,a) \;\simeq\; k\,a\,[1 \,-\, \alpha\,(k\,a)^2/2] \,+\, 2\,\pi^2\,h^{-2}\,k^{-1}\,a\,m^2\,c^2 \tag{5}$$

and, in any case, we expect observable kinematical effects when the term $\alpha(ka)^3/2$ becomes as large as the term $2\,\pi^2\,h^{-2}\,k^{-1}\,a\,m^2\,c^2$. This happens at:

$$E \;\simeq (2\pi)^{-1}\,h\,c\,k \;\approx\; \alpha^{-1/4}\,(h\,c\,a^{-1}/2\pi)^{1/2}\,(m\,c^2)^{1/2} \tag{6}$$

Thus, contrary to conventional estimates of local Lorentz symmetry breaking predictions (Anchordoqui, Dova, Gómez Dumm and Lacentre, 1997) where the modification of relativistic kinematics is ignored, observable effects will be produced at wavelength scales well above the critical length. For a proton or a neutron, and taking $a \;\approx\; 10^{-33}\;cm$, this corresponds to $E \;\approx 10^{19}\;eV$, an energy scale below the highest energies at which cosmic rays have been observed. Similar considerations apply to nuclei and would apply to muons, pions and τ leptons if these particles were stable. It must be realized that, for a proton at $E \;\approx\; 10^{20}\;eV$ and with the above value of a , one would have:

$$\alpha\,(k\,a)^2/2 \;\approx\; 10^{-18} \;\gg\; 2\,\pi^2\,h^{-2}\,k^{-2}\,m^2\,c^2 \;\approx 10^{-22} \tag{7}$$

so that, although $\alpha(ka)^3/2$ is indeed very small as compared to the value of $e\;(k\;a)$, the term $2\;\pi^2\;h^{-2}\;k^{-1}\;a\;m^2\;c^2$ represents an even smaller fraction of this quantity. We therefore expect corrections to relativistic kinematics to play a crucial role at the highest cosmic ray energies. Although Lorentz symmetry certainly reflects to a very good approximation the reality of physics at large distance scales and can therefore be considered as the low-energy limit of particle kinematics, no existing experimental result proves that it applies with the same accuracy to high-energy cosmic rays. In view of the above considerations, the question deserves serious practical study in close connexion with high-energy experiments. In what follows, we discuss two expected consequences of local Lorentz symmetry violation, assuming the value of c in (1) to be a universal constant.

THE GZK CUTOFF DOES NO LONGER APPLY

A proton with $E \;>\; 10^{20}\;eV$ interacting with a cosmic microwave background photon would be sensitive to the above corrections to relativistic kinematics. For instance, after having absorbed a $10^{-3}\;eV$ photon moving in the opposite direction, the proton gets an extra $10^{-3}\;eV$ energy, whereas its momentum is lowered by $10^{-3}\;eV/c$. In the conventional scenario with exact Lorentz invariance, this is enough to allow the excited proton to decay into a proton or a neutron plus a pion, losing an important part of its energy. However, it can be checked (Gonzalez-Mestres, 1997) that in our scenario with Lorentz invariance violation such a reaction is strictly forbidden. Elastic $p \,+\, \gamma$ scattering is permitted, but allows the proton to release only a small amount of its energy. The outgoing photon energy for an incoming $10^{20}\;eV$ proton cannot exceede $\Delta E^{max} \;\approx 10^{-5}\;E \;=\; 10^{15}\;eV$ instead of the value $\Delta E^{max} \;\approx\; 10^{19}\;eV$ obtained with exact Lorentz invariance. Similar or more stringent bounds exist for channels involving lepton production. Furthermore, obvious phase space limitations will also lower the event rate, as compared to standard calculations using exact Lorentz invariance which predict photoproduction of real pions at such cosmic proton energies. The effect seems strong enough to invalidate the Greisen-Zatsepin-Kuzmin cutoff (Greisen, 1966; Zatsepin and Kuzmin, 1966) and explain the existence of the highest-energy cosmic rays. It will become more important at higher energies, as we get closer to the a^{-1} wavelength scale. Similar arguments apply to heavy nuclei, again invalidating the GZK cutoff. Since, in both cases, the cosmic ray energy was expected to degrade over distances $\approx 10^{24}\ m$ according to conventional estimates, the correction by several orders of magnitude we just introduced applies to distance scales much larger than the estimated size of the presently observable Universe. Obvioulsy, our result is limited by the history of the Universe, as cosmic rays coming from distances closer and closer to c^{-1} times the horizon size will be older and older and, at early times, will have been confronted to rather different scenarios. Nevertheless, the above modification of relativistic kinematics allows much older cosmic rays to reach earth nowadays.

A previous attempt to explain the experimental absence of the predicted GZK cutoff by Lorentz symmetry violation at high energy (Kirzhnits and Chechin, 1972) led the authors to consider an expansion in powers of γ^4, where $\gamma = (1 - v^2c^{-2})^{-1/2}$, v is the speed of the particle and the coefficient of the linear term in γ^4 had to be arbitrarily tuned to $\approx 10^{-44}$ in order to produce an effect of order 1 for a $10^{20}\ eV$ proton (therefore leading to a divergent expansion at higher energies). No such problems are encountered in our approach, where the required orders of magnitude come out quite naturally. If the absence of GZK cutoff is indeed due to the kinematics defined (1), it allows in principle to set a lower bound on the value of the fundamental length (around $10^{-34}\ cm$).

UNSTABLE PARTICLES MAY BECOME STABLE AT VERY HIGH ENERGY

In standard relativity, we can compute the lifetime of any unstable particle in its rest frame and, with the help of a Lorentz transformation, obtain the Lorentz-dilated lifetime for a particle moving at finite speed. The same procedure had been followed in previous estimates of the predictions of local Lorentz symmetry breaking (Anchordoqui, Dova, Gómez Dumm and Lacentre, 1997) for the decay of high-energy particles. This is no longer possible with the kinematics defined by (1). Instead, two results are obtained (Gonzalez-Mestres, 1997):

i) Unstable particles with at least two massive particles in the final state of all their decay channels become stable at very high energy, as a consequence of Lorentz symmetry violation through (1). A typical order of magnitude for the energy E^{st} at which such a phenomenon occurs is:

$$E^{st} \approx c^{3/2}\ h^{1/2}\ (a\ m_2)^{-1/2}\ (m^2 - m_1^2 - m_2^2)^{1/2} \tag{8}$$

where: a) m is the mass of the decaying particle; b) we select the two heaviest particles of the final product of each decay channel, and m_2 is the mass of the lightest particle in this list; c) m_1 is the mass of the heaviest particle produced together with that of mass m_2. With $a \approx 10^{-33}\ cm$, **the neutron would become stable** for $E \gtrsim 10^{20}\ eV$. At the same energies or slightly above, **some unstable nuclei would also become stable**. Similarly, **some hadronic resonances** (e.g. the Δ^{++}, whose decay product contains a proton and a positron) **would become stable** at $E \gtrsim 10^{21}\ eV$. Most of these objects will decay before they can be accelerated to such energies, but they may result of a collision at very high energy or of the decay of a superluminal particle (Gonzalez-Mestres, 1996). The study of very high-energy cosmic rays can thus reveal as stable particles objects which would be unstable if produced at accelerators. If one of the light neutrinos (ν_e, ν_μ) has a mass in the $\approx 10\ eV$ range, **the muon would become stable** at energies above $\approx 10^{22}\ eV$. Weak neutrino mixing may restore muon decay, but with very long lifetime. **Similar considerations apply to the τ lepton**, which would become stable above $E \approx 10^{22}\ eV$ if the mass of the ν_τ is $\approx 100\ eV$ but, again, a decay with very long lifetime can be restored by neutrino oscillations.

ii) In any case, unstable particles live longer than naively expected with exact Lorentz invariance and, at high enough energy, the effect becomes much stronger than previously estimated (Anchordoqui, Dova, Gómez Dumm and Lacentre, 1997) ignoring the small violation of relativistic kinematics. At energies well below the stability region, partial decay rates are already modified by large factors leading to observable effects. Irrespectively of whether m_2 vanishes or not, the phenomenon occurs at $E \gtrsim c^{3/2}\ h^{1/2}\ (m^2 - m_1^2)^{1/4}\ a^{-1/2}$ ($\approx 10^{18}\ eV$ for $\pi^+ \rightarrow e^+ + \nu_e$, if $a \approx 10^{-33}\ cm$). The effect has a sudden, sharp rise, since a fourth power of the energy is involved in the calculation.

CONCLUDING REMARKS

For similar reasons, a small violation of the universality of c would not necessarily produce the Cherenkov effect in vacuum considered by Coleman and Glashow (1997) for high-energy cosmic rays. The mechanism we just described competes with those considered in their discussion and tends to compensate their effect: therefore, the bounds obtained by these authors do not apply to our ansatz. On the other hand, the discussion of velocity oscillations of neutrinos presented by Glashow, Halprin, Krastev, Leung and Pantaleone (1997) for the low-energy region is compatible with our theory. However, the universality of c seems natural in most unified field theories (whereas that of the mass is naturally violated) and preserves the Poincaré relativity principle (Poincaré, 1905) in the low-momentum limit. In any case, if Lorentz symmetry is broken and an absolute rest frame exists, high-energy particles are indeed different physical objects from low-energy particles.

It is also interesting to lower the value of a^{-1} down to the wave vector of the highest-energy cosmic rays, $\approx 10^{25}\ cm^{-1}$. Then, a stable neutron is predicted at energies $\gtrsim\ 10^4\ TeV$ and, with respect to the above estimates for other particles, the energy threshold for stability is to be lowered by a factor $\approx\ 10^{-4}$. For similar reasons, the departure from standard relativistic values for partial decay rates would start at $E\ \gtrsim\ 100\ TeV$ for the $\pi^+ \rightarrow e^+ + \nu_e$ channel. Not only lifetimes do not follow relativistic formulae, but partial branching ratios become energy-dependent and are sensitive to the masses of the produced particles. Data on high-energy cosmic rays contain information relevant to these phenomena and should be carefully analyzed. Cosmic rays seem to indeed be able to test the predictions of (1) and set upper bounds on the fundamental length a . Experiments like AUGER and AMANDA present great potentialities in this respect. Very high-energy data may even provide a way to measure neutrino masses and mixing, as well as other parameters related to phenomena beyond the standard model. Even if the energy is in principle too low, lifetime measurements at LHC energies are also worth performing. Because of its stability at very high energy, the neutron becomes a serious candidate to be a possible primary of the highest-energy cosmic ray events.

ACKNOWLEDGEMENTS

It is a pleasure to thank J. Gabarro-Arpa, as well as colleagues at LPC Collège de France, for useful discussions and remarks.

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