

High-energy cosmic rays and tests of basic principles of Physics

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Abstract - With the present understanding of data, the observed flux suppression for ultra-high energy cosmic rays (UHECR) at energies above $4 \cdot 10^{19}$ eV can be a signature of the Greisen-Zatsepin-Kuzmin (GZK) cutoff or correspond, for instance, to the maximum energies available at the relevant sources.

In both cases, violations of standard special relativity modifying cosmic-ray propagation or acceleration at very high energy can potentially play a role.

Last AUGER data : [arXiv:1202.1493](https://arxiv.org/abs/1202.1493) , [arXiv:1201.6265](https://arxiv.org/abs/1201.6265)

Thus, UHECR data would in principle allow to set bounds on Lorentz symmetry violation (LSV) in patterns incorporating a privileged local reference frame (the "vacuum rest frame", VRF).

But the precise analysis is far from trivial, and other effects can also be present.

The effective parameters can be related to Planck-scale physics, or even to physics beyond Planck scale, as well as to the dynamics and effective symmetries of LSV for nucleons, quarks, leptons and the photon. LSV can also be at the origin of GZK-like effects.

In the presence of a VRF, LSV can modify the internal structure of conventional particles at very high energy and standard symmetries may cease to be valid at energies close to the Planck scale.

(Contrary to a « grand unification » view)

Other fundamental principles and conventional basic hypotheses (quantum mechanics, quark confinement, energy and momentum conservation, vacuum homogeneity and "static" properties, effective space dimensions...) can be violated at such scales, possibly leading to effects that can be tested in high-energy cosmic-ray experiments.

Contrary to standard pictures of UHE Physics, one can imagine scenarios where symmetries would not become all the time more and more exact as energy increases, and the contrary would start happening above some critical energy scale below Planck scale.

=> New potentialities for high-energy cosmic ray phenomenology

=> Possible link with unconventional pre-Big Bang scenarios, superbradyon (superluminal preon) patterns...

We present an updated discussion of these topics, including experimental prospects and possible new interpretations of the observed UHECR composition in terms of LSV mechanisms where, for instance, the GZK cutoff would be replaced by spontaneous emission of photons or $e^+ e^-$ pairs.

The subject of a possible superluminal propagation of neutrinos at accelerator energies is also dealt with, considering bounds from possible theoretical and phenomenological inconsistencies. (end of abstract)

OPERA claim of september 2011: arXiv:1109.4897

Now the result has been withdrawn. Consistency problems pointed out since last september.

Work on consistency problems : was it enough frame-independent to yield a significant result ?

The relativity principle

Henri Poincaré, 1895

"A propos de la théorie de M.Larmor"

L'Eclairage électrique, Vol. 5, 5.

"Absolute motion of matter, or, to be more precise, the relative motion of weighable matter and ether, cannot be disclosed. All that can be done is to reveal the motion of weighable matter with respect to weighable matter".

St Louis 1904 : c (speed of light), universal critical speed ; relativity also applies to kinematics and mechanics => special relativity

Also, Lorentz (1904) = explicit v (speed) $< c$

Possible Lorentz symmetry breaking through scale-dependence

Albert Einstein, 1921

***Geometry and Experiment* (English, 1922)**

"It is true that this proposed physical interpretation of geometry breaks down when applied immediately to spaces of sub-molecular order of magnitude. But nevertheless, even in questions as to the constitution of elementary particles, it retains part of its importance. For even when it is a question of describing the electrical elementary particles constituting matter, the attempt may still be made to ascribe physical importance to those

ideas of fields which have been physically defined for the purpose of describing the geometrical behaviour of bodies which are large as compared with the molecule. Success alone can decide as to the justification of such an attempt, which postulates physical reality for the fundamental principles of Riemann's geometry outside of the domain of their physical definitions. It might possibly turn out that this extrapolation has no better warrant than the extrapolation of the idea of temperature to parts of a body of molecular order of magnitude”

Source :

MacTutor History of Mathematics Archive

Presently available wavelengths are far beyond...

... molecular distance scales, and no well-established violation of relativity yet found !

What to do ?

Follow Einstein's reasoning : Try to apply, try to break, make measurements... and see what happens => **Cosmic-ray experiments** => **Relativity** is not the only fundamental principle to test.

arXiv:physics/9704017, arXiv:1202.1277 , arXiv:1109.6630 ,
arXiv:1109.6630 , arXiv:1011.4889 , arXiv:1009.1853 ,
arXiv:0908.4070 , arXiv:0902.0994 , arXiv:physics/9712047,
arXiv:physics/9705031 , arXiv:astro-ph/9606054 **and**
previously : arXiv:astro-ph/9505117, arXiv:astro-ph/9601090

Other fundamental principles to test

- **Quantum mechanics – Standard uncertainty principle, ...**
- **Vacuum homogeneity, validity of quantum field theory...**
- **Energy and momentum conservation as a consequence of space-time translation invariance**
- **(At least) four effective space-time dimensions**
- **(CPT, Lagrange-Hamilton, vacuum...)**
- **(...)**

Models of Lorentz symmetry violation (LSV) that can be tested by UHCR.

Example, QDRK (Quadratically deformed relativistic kinematics)

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

$$e^2 (k a) \simeq (k a)^2 - \alpha (k a)^4 + (2 a)^2 h^{-2} m^2 c^2$$

k = wave vector, a = fundamental length

Expansion for $ka \ll 1$, $\alpha (ka)^4$ generates LSV

New physics when $\alpha (ka)^4$ becomes of the same order as the mass term $(2 a)^2 h^{-2} m^2 c^2$

Needs an absolute (vacuum) rest frame (VRF)

Otherwise : no observable effect for UHECR (go to the center of mass frame, corrections to SR too small)

Example of new physics :

Possible suppression of the GZK cutoff.

Kirzhnits, D.A., and Chechin, V.A. (1972) => deformation from Lorentz to a Finsler algebra, failed basically because there was no privileged reference frame.

Gonzalez-Mestres (1996) => Cherenkov radiation in vacuum from UHE superluminal particles, arXiv:astro-ph/9606054

Gonzalez-Mestres (1997) => Deformation of standard Lorentz symmetry (QDRK) in patterns with an absolute rest frame (VRF) => arXiv:physics/9704017 , ICRC arXiv:physics/9705031

=> also : particles that are unstable at low energy can become stable at very high energy ; other effects suggested in subsequent papers

For other approaches to LSV and to tests of Lorentz symmetry, see for instance, J. Ellis, N.E. Mavromatos, arxiv: 1111.1178 :

“Lorentz invariance is such an important principle of fundamental physics that it should constantly be subjected to experimental scrutiny as well as theoretical questioning”.

In QDRK => transition region $E \approx E (trans)$ where :

$$\alpha (k a)^4 \approx (2 a)^2 h^{-2} m^2 c^2$$

**Above $E (trans)$ kinematical balances are modified
=> the GZK cutoff would disappear because of **the new cost in energy to split p** generated by the term
 $- p c (k a)^2/2$ in the dispersion relation.**

BUT QUESTIONS : What is the right value of α for each particle ? What is the « fundamental » value of α for standard matter ?

=> take protons and/or nuclei, or quarks and gluons ? Estimate the difference.

Is the fundamental scale exactly the Planck scale ?

See CRIS 2008 and CRIS 2010 Proceedings

Data do not necessarily exclude « maximal » LSV with $\alpha \approx 0.1 - 1$ for quarks and gluons, $a = \text{Planck length} \Rightarrow \text{UHECR composition and sources ?}$

Gonzalez-Mestres, 1997 : « For $\alpha a^2 > 10^{-72} \text{ cm}^2$, and assuming a universal value of α , the GZK cutoff is suppressed for the particles under consideration and ultra-high energy cosmic rays (e.g. protons) produced anywhere in the presently observable Universe can reach the earth without losing their energy in collisions with the cosmic microwave background radiation » ($\alpha > 10^{-6}$ if $a = \text{Planck length}$) BUT :

It was actually assumed that the highest-energy cosmic rays are protons \Rightarrow If so, this is the upper bound on α (*proton*) from the possible existence of the GZK cutoff

For large systems, α proportional to M^{-2} in order to get a consistent QDRK + Extra M^{-2} when comparing the deformation with the term M^2/p (Gonzalez- Mestres, arxiv:nucl-th/9708028 ...)

=> Similar for protons and nucleons in terms of quarks and gluons ?

=> « Ultimate » α >> « effective » α

Gonzalez-Mestres, 1997 : If *particle 1* has a positive value of α larger than that of *particle 2*, *particle 2* can decay into *particle 1* + (...) at high enough energy ($p \rightarrow p + \gamma$).

But : i) often dynamically difficult ; ii) time dilation => In general, very slow process =>

f.i. can the decays $p \rightarrow p + \gamma$, $N \rightarrow N + \gamma$ replace the GZK cutoff for protons and nuclei ?

Possible suppression of photons by $\gamma \rightarrow e^+ e^-$?

=> LORENTZ SYMMETRY VIOLATION CAN SUPPRESS THE GZK CUTOFF, BUT IT CAN ALSO GENERATE MECHANISMS FAKING IT

Gonzalez-Mestres, 1997 and 2000 (arXiv:astro-ph/0011182) : possible **suppression of synchrotron radiation by LSV** in UHE cosmic accelerators due to the negative deformation energy of the accelerated particle
=> New experimental tests ?

Pierre Auger Collaboration, February 2010 : “... a suppression of the flux with respect to a power law extrapolation is found , which is compatible with the predicted Greisen-Zatsepin-Kuz'min (GZK) effect, but could also be related to the maximum energy that can be reached at the sources.”

=> UHECR MASS COMPOSITION, A CRUCIAL ISSUE FOR TESTS OF LORENTZ SYMMETRY AND OF LSV PATTERNS

Pierre Auger Collaboration, January 2012 : “At low energies, the shape of the data distribution is compatible with a very light or mixed composition, whereas at high energies a heavier composition is favored.”

- Observation of the GZK cutoff for heavy nuclei => a weak bound on the primordial α of quarks**
 - There may exist LSV alternatives to the GZK explanation of data (spontaneous decays...)**
- => FURTHER EXPERIMENTAL INFORMATION NEEDED**

OTHER FUNDAMENTAL PRINCIPLES AND LAWS

(QDRK and superbradyons are just tools)

QUANTUM MECHANICS - There has already been important work on possible departures from standard quantum mechanics : f.i. Julius Wess, q-Deformed Heisenberg Algebras, arXiv:math-ph/9910013 (see also the references given in Gonzalez-Mestres, arXiv:0908.4070 and CRIS 2010).

Standard relativity is not the only fundamental principle concerned => Quantum mechanics can be « deformed » in a similar way.

CODATA value of h : $6.62606957 \times 10^{-34} \text{ J s}$ with a 4.4×10^{-8} standard accuracy and **based on low-energy measurements**
=> what at ultra-high energies, ultra-short distances ?

Develop the equivalent of QDRK for quantum mechanics ?

=> New commutation relations, where the effect of the modification increases with energy

=> can lead, for instance, to unexpected intrinsic uncertainties (direction, momenta, energy...)=> Potentially observable effects at UHECR

More basically, for instance : can hamiltonian and lagrangian formalisms describe the behaviour of vacuum at ultra-short distance scales ? Is vacuum « homogeneous » ? Etc...

Similarly, a very small failure of energy and momentum conservation at ultra-high energies can possibly fake the Greisen – Zatsepin – Kuzmin cutoff. And what is the vacuum « doing » at such ultra-short wavelengths ?

Would superbradyons (superluminal preons) and similar objects obey quantum mechanics ? Or is quantum mechanics a « composite » phenomenon ?

And many other similar questions...

Do standard symmetries and laws of Physics become more and more precise as one gets close to Planck scale, or does this evolution change above some energy scale ? => Possible unexpected role of extrapolations from « pre-Big Bang » Physics

SUPERBRADYONS $c_s \gg c$ (1995)

$$E_s = c_s (p_s^2 + m_s^2 c_s^2)^{-1/2} \text{ (if new Lorentz symmetry)}$$

$$p_s = m_s v_s (1 - v_s^2 c_s^{-2})^{-1/2}$$

« Cherenkov radiation » in vacuum for $v_s > c$ => spontaneous emission of « conventional » particles.

Needs compatibility with low-energy bounds on LSV. Must preserve conventional relativity in the "low-energy limit".

=> Ultra-high energy phenomenon. Can they emit UHECR beyond GZK (arXiv:astro-ph/9606054)? Superbradyonic remnants at $v \simeq c$ may exist in the present universe and play a cosmological role => Dark matter, dark energy ?

THE SEPTEMBER 2011 OPERA NEUTRINO

OPERA : arXiv:1109.4897 (September 22)

Possible consistency problems :

Gonzalez-Mestres, september 28, arXiv:1109.6308 , **i) spontaneous decays of the neutrino ; ii) problem of pion critical speed.**

Cohen and Glashow, september 29, arXiv:1109.6562 , **very detailed calculation confirming the spontaneous decay problem**

Gonzalez-Mestres, september 29, arXiv:1109.6630 , **confirming the pion problem** : the extra neutrino speed implies extra energy that the pion should provide from its own kinematics. Then, **the anomaly spreads to hadrons. See also : arXiv:1202.1277**

=>After these first three papers, several analyses by other authors. **Basic contradiction between our knowledge of particle Physics and Astrophysics up to the 10^{20} eV scale and such a strong effect at much lower energies.** Calculations tacitly used a preferred rest frame, but the basic result does not seem to really depend on it.

=> Also, using SN1987a data : J. Alexandre, J.Ellis, N.E. Mavromatos, arXiv:1109.629 (September 28)

TO CONCLUDE :

Cosmic-ray experiments have extraordinary and unprecedented discovery potentialities

UHECR experiments are a powerful microscope directly focused on the Planck scale and beyond.

Long-term experimental programs and permanent observatories are required, allowing for better statistics with more precise analyses and theoretical studies.

All basic principles of standard particle physics should be tested in this way.

=> Combine UHECR experiments with fundamental cosmology observations (Tuesday talk)