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# Fermi acceleration mechanisms under Lorentz violating physics.

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**Abstract.** The theory of relativity has significantly transformed our understanding of space and time, establishing itself as a cornerstone in modern physics. Nevertheless, certain high-energy models may indicate divergences, prompting the proposal and analysis of Lorentz invariance violation (LIV). In this study, we explore the first and second order Fermi acceleration mechanisms, incorporating the framework of Lorentz invariance violation, and derive new cosmic ray spectra in each scenario.

**Resumo.** A teoria da relatividade mudou drasticamente a forma como entendemos o espaço e o tempo, tornando-se uma das fundações da física moderna. Entretanto, alguns modelos de altas energias apontam para uma possível divergência, resultando na proposta e análise da quebra de invariância de Lorentz (VL). Neste trabalho, estudamos o mecanismo de aceleração de Fermi de primeira e segunda ordem, adicionando a hipótese de quebra de invariância de Lorentz, assim obtendo um novo espectro de raios cósmicos em cada cenário.

**Keywords.** Relativistic processes – cosmic rays – Acceleration of particles

## 1. Introduction

Einstein first published the theory of relativity in 1905, and since its formalization, it has become one of the building blocks of modern theories and discoveries. However, in high-energy models of the universe, theoretical considerations suggest the potential for a break in Lorentz symmetry, resulting in a modification of the energy dispersion relation:

$$E^2 = m^2 + p^2 + \delta_n p^n. \tag{1}$$

This often leads to a violation of Lorentz symmetry, giving rise to new effects such as vacuum Cherenkov radiation and photon time delay Mattingly (2005).

This violation is a central component in some quantum gravity theories; thus, it is expected and theorized that its contributions would be noticeable only at the Planck energy,, $E_{Planck} \approx 10^{19} GeV$, an scale where gravity and quantum mechanics should be unified. Our best candidates for observing the predicted effects are the cosmic rays, the most energetic particles known.

It's important to know how the highest-energy cosmic rays gain their energy. Fermi initially suggested a straightforward explanation involving collisions, later recognized as the second-order Fermi mechanism Fermi (1949). Subsequently, independent researchers, including Bell and Drury, identified an efficient acceleration process known as diffusive shockwave acceleration, referred to as the first-order Fermi mechanism, where particles would gain energy via a succession of passages through the discontinuity of the shock Drury (1983).

Both channels rely on Lorentz invariance, transforming them into important tools for symmetry violation tests.

## 2. Second order Fermi mechanism.

We focus on extremely high energies, that way we can write equation (1), with no loss of generality, as

$$E = p\sqrt{1 + \delta_n p^n} \approx p\sqrt{1 + \delta_n E^n}. \tag{2}$$

For the second order Fermi mechanism, we may consider a particle colliding with a gas cloud moving with respect to the lab with velocity $\vec{V}$, then, performing two Lorentz transformations:

$$E' = \gamma(E + Vp\cos\theta), \tag{3}$$

$$E'' = \gamma(E' + Vp'\cos\theta'). \tag{4}$$

Using equation (2) in (3) and (4), it's possible to obtain the new net gain,

$$\left\langle \frac{\Delta E}{E} \right\rangle = 2\left[1 + \frac{1}{3\sqrt{1 + \delta_n E^n}}\right]\left(\frac{V}{c}\right)^2. \tag{5}$$

Having the energy gain, we may use the diffusion-loss equation,

$$\frac{N}{\tau_{scp}} + \frac{\partial N}{\partial t} = \frac{\partial}{\partial E}(bN) + D\nabla N + Q(E), \tag{6}$$

to obtain the spectrum leaving the source. We seek an steady-state solution, so $\frac{\partial N}{\partial t} = 0$, there is no diffusion, $D\nabla N = 0$, and no injection, $Q(E) = 0$, therefore, considering that

$$b = -\frac{dE}{dt} \approx -\frac{\langle \Delta E \rangle}{\Delta t} = -\frac{\langle \Delta E \rangle}{\tau_{int}}, \tag{7}$$

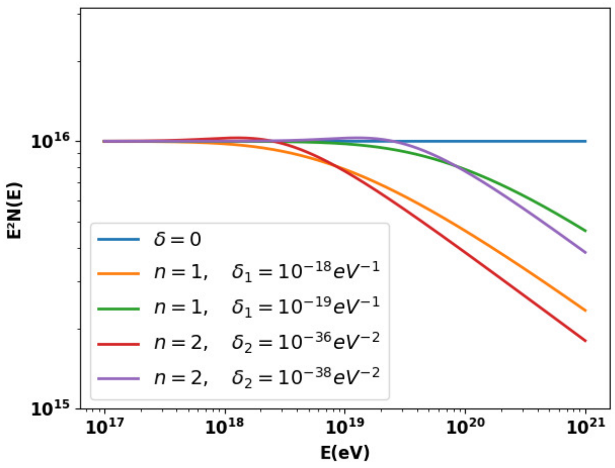


Figure 1: Spectrums for the second order Fermi acceleration. Blue line is the no-LIV scenario. The value of $\frac{\tau_{scp}}{\tau_{int}} = \frac{8}{3}$ was adopted in order to the index match the value of -2.

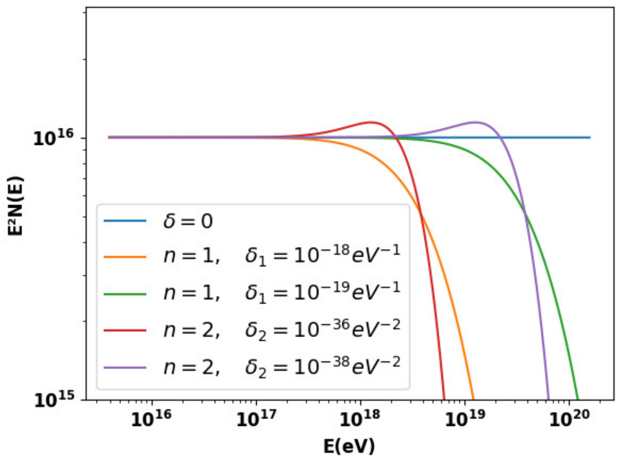


Figure 2: Spectrums, numerically obtained, for the first order Fermi acceleration. Blue line is the no-LIV scenario for comparison.

we are able to derive the new spectrum, where $\tau_{scp}, \tau_{int}$ are the scape time of the acceleration region and the characteristic collision time, respectively. Those will turn into one free parameter. Solving it numerically,

We can see a deviation from the standard spectrum, in a way that the variation is shifted by the parameter $\delta_n$ and the shape of the curve is defined by n.

For the second order accelaration, this is not the full picture; we also need to consider stochastisc gains, coming from a more fundamental relation, the Vlasov relativistc equation Blandford& Eichler (1987).

## 3. First order Fermi mechanism.

Another system was, later, proposed, based on Shockwaves. If we consider a diffusive shockwave propagating with velocity $V$, we may perform a Lorentz transformation each time a particle crosses the shock. That way, the new energy gain in the Lorentz violation framework becomes

$$\left\langle \frac{\Delta E}{E} \right\rangle = \frac{4}{3\sqrt{1+\delta_n E^n}} \left( \frac{V}{c} \right). \tag{8}$$

Again, we will use equation (6) and (7) in order to obtain the new spectrum. Due to the nature of the shockwave, we may consider the scape probability of the accelerated particle, resulting in the following relation:

$$\tau_{scp} = \langle n\tau_{int} \rangle = \sum_{n=1}^{\infty} = n\tau_{int} P^{(n-1)}(1-P). \tag{9}$$

Now $\frac{\tau_{scp}}{\tau_{int}}$ is no longer a free parameter and perfectly produces the Lorentz Invariance scenario index of -2. Creating the new spectrum, represented in figure (2),

The same behaviour is present in this model. The energy in which the break of the symmetry is evident is dictated by the parameter $\delta_n$ while the shape of the spectrum is n-dependent, except this time we no longer need an extra parameter defined by scape and interaction times.

## 4. Conclusions.

From the modified energy dispersion relation we were able to derive a new cosmic ray spectrum, both for the first and the second order mechanisms. In both scenarios, the same behaviour was seen, excluding the fact that the second order mechanism needs one extra parameter. Some details are to be considered further, such as propagation and composition.

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