Violation of Lorentz invarinace and Absolute frame of the Expanding

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GZK-cutoff is based on the principle of relativity, that claims the non-existing of any physically prefereble inertia frame in the universe. On contray to this principle since Galileo, some prefereble inertia frame in the expanding universe can be identified, such Absolute frame as CMB- and H-isotropic frame and rest frame of matter or astronomical objects. One of the challenge of EHE cosmic-rays experiment is to seek a footprint on physics law of this Absolute frame.

KEYWORDS: cosmic rays, GZK-cutoff, relativity principle, Lorentz invariance

§1. Historical Introduction

In the fall of 1971, the japanese cosmic-ray researchers heard an exciting news from the Air-shower group led by K. Suga. They claimed that their air shower array in Tanashi(in Tokyo) had catched a big event, whose enery was estimated to be well above the GZK-cutoff energy.$^{1)}$ The workshop was suddenly organized at ICRR to discuss the implication of this discovery. Along with the discussion to check the observational result, there were also some discussions on the theoretical implication of super GZK-cutoff. The proceeding of this workshop was published in the japanese journal "*Uchuusen Kenkyuu*" (Cosmic Rays in english).

In order to avoid the conflict between theoretical prediction and the observational result, three possible ways were pointed out;

1) local origin
2) exotic composition(not proton)
3) violation of relativity.

This analysis concerning the super GZK-cutoff problem is still true even now. The first point was mainly concerned with the anisotropy at the time. As to the second point above, "heavy particle" such as nuclei and dust as well as neutrino were discussed. I remenmber S. Hayakawa proposed even relativistic dusts model. At that workshop, I proposed the third point and ,later, wrote the paper, titled "Hot Universe, Cosmic Rays of Ultrahigh Energy and Absolute Reference System".$^{2)}$

In the beginning part of this paper published in 1972, I mentioned that "If the attenuation(cutoff) were really found experimentally, it might be a remarkable evidence to expand the applicable realm of the relativity principle", upto the Lorentz factor of $\gamma \sim 10^{11}$ relative to our laboratory reference system. In the later part of this paper, I added one concrete example to show how the violation of relativity principle could affect the result of GZK-cutoff. The Lorentz-violating cutoff theory proposed by T. Tati, who had considered this cutoff theory in a different contexst of physics, was adopted for this discussion.

§2. Relativity principle and GZK-cutoff

The relativity principle that claimes non-existence of a preferable inertia reference frame in the universe has long been the most fundamental axiom in physics since Galileo. Einstein's relativity had kept the same spirit of this axiom and had changed only the transformation formula connecting the equivalent inertia frames from the Galileo transformation into the Lorentz transformation.

In the discussin to introduce the GZK-cutoff, this relativity principle has been taken for granted of course, in such manner that the interaction cross section ,σ,is a function of the invarianat four momenta,Q. That is, $\sigma = \sigma(Q)$ and $Q^2 = (P_{(1)} + P_{(2)})^\mu (P_{(1)} + P_{(2)})_\mu$, $P_{(a)}$ being four momentum of interacting particles (a). Violation of the relativity principle claimes in some sense that the cross section takes a form of $\sigma(P_{(1)}, P_{(2)})$ or $\sigma(Q, P_{(1)})$ for example, where $P_{(a)}$ is the values in the preferable frame S_0, whose characterization will be given later.$^{3)}$ The violation of relativity principle is to assume such preferable Absolute reference frame and the frame S moving with γ relative to S_0 is no more identical with S_0, γ being the Lorentz factor.

Of course , it is true that ,through various theories and experiments, we have not found , up to now, any difference between S_0 and the frames $S(\gamma)$. Even so, the essential difference of $S(\gamma)$ from S_0 might reveal itself in the new phenomena which involves an extraordinary large γ. In this line of consideration, the GZK-cutoff in which the frame $S(\gamma = 10^{11})$ is involved is one of such phenomena.

If the absolute reference frame would exist, the basis of GZK-cutoff would be suspended. On the contrary, if GZK-cutoff would be clearly observed as this argument predicts, then, the experimental verification of the relativity principle could be said to be extended up to $\gamma \sim 10^{11}$ relative to S_0. This was the point of my paper in 1972.$^{2)}$

§3. Absolute frame in the Expanding Universe

In these several years, the interest concerning GZK-cutoff has revived since the observational evidences of super GZK-cutoff cosmic rays were reported by AGASA and Fly's Eyes. In that trend, several arguments to connect GZK-cutoff with the violation of relativity principle have appeared again, with a long interval of a quater of century after my paper in 1972. It is interesting to rise a quetion whether there were some progress in physics during this interval, which forces us to be more suspicious about the relativity principle. I think we have both anwsers, *no* and *yes*.

Why *no*? Because the so-called standard model of interaction based on gauge theory and quark-lepton is so successfull, all sort of doubt about the Lorentz-invarianat quantum field theory had disappeared. And all of the old attempts such as cutoff-length theory to avoid the divergence were cleaned away from the major scene of physics. Then, *no* answer will be a view spread widely after the settlement of the standard theory.

Then, why *yes*? Since the further extension of the satndard theory predicts some unification of matter and spacetime, the comoving local inertia frame in the expanding universe might have some prefereed status among the others. Of course, in different from the above *no* argument, this *yes* argument is not wide-spread opinion but is rather minor opinion, on which I will explain shortly in the followings.$^{4)}$

The study of the early satage of Big Bang Universe has taught us that the creation(or excitaion) of matter has chosen the local comoving inertia frame as a preferered frame. This frame seems to be identical with the CMB isotropic frame. That is, the following three frames are approximately identical:

a) Hubble-expansion isotropic frame,
b) CMB isotropic frame,
c) matter-at-rest frame.

The small differences among them at present are explained by the evolution of the fluctuation and it is clear that some unique preferable frame has been chosen. This is understandable since both matter and CMB are originated by quantum excitaion from the vacuum, may be at the terminal period of the Inflation.Then it is true that a preferable frame can be definitely identified in all points of spacetime in our universe.

This kind of arguments would invoke the *yes* answer. Of course, the above identification does not directly imply the violation of relativity prinicple. However this may provide a valuable clue to dig its further implication.

§4. Particle Transformation and Hidden External Fields

Usually the relativity principle is defined as the invariance of Lagrangian under the Lorentz transformation. There are two ways of expressing this invariance; one is *passive* transformation, which implies an invariance of the same phenomena under the transformation of observer, and another one is *active* transformation, which implies an ivariance of the transformed phenomena with the original one. But, if we transform all the components of the system, the difference does not appear. And the above classification of *passive* and *active* has no useful meaning. However, if we restrict the *passive* transformation soley to the four-momentum of particles, the *passive* and *active* transformations differs for the situations under the external fields. This new modified transformation of *passive* transformation is not exactly the Lorentz tranformation any more and we call it *particle* transformation.$^{5)}$

It is evident that the invariance of motions under the external field is violated under the *particle* transformation in general. The motion of two particles whose energies are related by the boost transformation will be different in general in the external fields. That is , the invariance under the *particle* transformation is violated. But, of course, people would say that the *particle* transformation should not be confused with the genuine Lorentz transfomation, where the external fields as well as the particle momentum must be transformed together in order to keep the Lorentz invaiance.

However, here, some complication comes in. The problem is how to check the absolute vacuum. Can we verify the non-existence of any external field even after we have subtracted all the known external fields in the actual cosmic space? We should realize that it is impossible to verify the genuine vacuum without knowing everything and it is also impossible to verify we have arlready known everything. Then the actual cosmic space subtracted all known kinds of the external fields might be not an clean empty space.

What we can do best is to prepair sub-empty space with possible hidden fields. If it were impossible to verify the complete cleanness of the spacetime and there were some remaining hidden external fields, even the Lorentz tranformation solely for all the explicitly known components would be a sort of *particle* tranformation effectively.

In the paradigm of the unified theory of matter and spacetime such as String Theory, the theory predicts a lot of redundant perturbtive fields, those are not identified and not requested at all in the minimal unified gauge theory. If we remind such an underlining paradigm, it would be probable to expect some of such fields might have finite value and act as the hidden external fields.$^{6)}$ Then, the *active* tranformation for the all known components excluding the hidden fields will be erroneously interpreted as the Lorentz transformation.

§5. Origin of Lorentz-Violating Interaction terms

Coleman and Glashow have discussed a toy model that the Lorentz violating interaction term introduces "velocity mixing" of the particle at extraordinary in the absolute frame S_0.$^{7)}$ By adding the violating term, the conventional Lorentz invariant Lagrangian is modified as

$$L \to L + \partial_i \phi \epsilon \partial^i \phi$$

,where $i = 1, 2, 3$ and lacking time derivative , ϕ is a set of fields and ϵ is a matrix which does not commute with the mass matrix in L. By this modification, the single-particle energy-momentum eigenstates changes from the eigenstates of the mass matrix at low energy into the eigenstates of ϵ at high energy.

The equivalent modification can be written also as

$$L \to L + \partial_0\phi\epsilon\partial^0\phi.$$

We speculate that this violating terms could happen from the Lorentz invariant term via the spontaneous symmetry break down. For example, suppose such Lorentz invariant term as below

$$[\partial_\mu\phi\partial^\mu\Phi]\,\xi\,[\partial_\mu\Phi\partial^\mu\phi]\,.$$

Here, Φ is a hidden external field which associates with determining the vacuum state of the constituting particles of the present universe and can not be excited locally by the ordinary particles interaction at the present. Recently , people are introducing various such kind of field into cosmological discussion, e.g., inflaton fields, fields determining the cosmological vacuum term, so-called Quintessence, brane, and so on. Of course, they are introduced not to harm the Lorentz invariance. But, once such dynamical hidden entities are introduced, it would be difficult to keep the symmmetry exactly.

If this field takes spatially uniform value, then, the above term reduces into the Lorentz violating term with

$$\epsilon = \partial^0\Phi\xi\partial_0\Phi,$$

where the derivative ∂^0 is a derivative by the cosmic time perpendicular to the uniform cosmic 3-space. Here Φ is supposed to be changing only with cosmological timescale, that is, such as $\partial_0\Phi \sim H_0\Phi$, H_0 being the Hubble constant at present. Therefore, we can easily expect the smallness of ϵ, even if ξ is not exceptionally small.

§6. Phenomenology of Lorentz-invariance Violation

In spite of the current trend toward the unified theory such as stated in the preceeding sections, we should not be trapped into this paradigm too much. In order toattack such an enormous problem like the Violation of Lorentz invariance, mere phenomenological analysis is also important as well. The follwings are some such examples:

(a) Energy cut-off$^{2)}$

Before the renormalized field theory of gauge fields was established, many peoples tried the cutoff theory in order to avoide the divergence difficulty; the cutoff is introduced in the integral over the momentum space. Sometime a huge energy scale such as Planck mass is introduced in the Lorentz-invariant manner as in the string Theory. By this way, we can suppress some freedom with infinite invariant energy $Q^2(=E^2-\mathbf{p}^2c^2)$. Another way of cutoff is to introduce a large energy in S_0 rather than Q, by which the integral over momentum space restricted to finite region. This violates the Lorentz invariance but the effect of the violation reveales itself only for extraordinary phenomena inS_0.

(b) Light velocity and Limitting velocity$^{8)}$

There are two origin of special relativity: One is the mechanical equivalence among inertial frames for a ponderable matter, which introduces a limiting velocity $c_{\rm m}$. Another one is the electrodynamic relativity, which introduces the constant light velocity, $c_{\rm em}$. Combining these two physical contents, the action for a charged particle is written as

$$I = \int dt\left[-mc_{\rm m}^2(1-\frac{v^2}{c_{\rm m}^2})^{\frac{1}{2}} + \frac{e}{c_{\rm m}}A_\mu v^\mu\right]$$

$$+\frac{1}{8\pi}\int dx^3dt\left[\mathbf{E}^2 - (\frac{c_{\rm em}}{c_{\rm m}})^2\mathbf{B}^2\right]$$

Einstein's special relativity implies simply $c_{\rm m} = c_{\rm em}$ and the Lorentz invariance holds for the Lagrangian. The electromagnetic part of the above Lagrangian can be rewritten as

$$\frac{1}{8\pi}\left[\mathbf{E}^2 - (\frac{c_{\rm em}}{c_{\rm m}})^2\mathbf{B}^2\right] = \frac{1}{8\pi}\left[\mathbf{E}^2-\mathbf{B}^2\right] + \epsilon\frac{1}{8\pi}\mathbf{B}^2$$

with $\epsilon = (1-(\frac{c_{\rm em}}{c_{\rm m}})^2)$. The last term in the right hand side is not Lorentz invariant and various experimental check has constrained this ϵ as $\epsilon < 10^{-22}$.

Vacuum Cherenkov radiation and Photon decay

Coleman and Glashow$^{7)}$ pointed out that an exotic channel of particle processes opens in case of $c_{\rm m} \neq c_{\rm em}$ and high energy check of Lorentz violation will be possible: If $c_{\rm m} < c_{\rm em}$, the photon decay $\gamma \to e^+ + e^-$ is opened above the the threshold energy $E = 2m/\sqrt{(c_{\rm em}/c_{\rm m})^2-1}$, and , if $c_{\rm m} > c_{\rm em}$, the vacuum Cherenkov radiation of charged particle become possible for the energy above $m/\sqrt{1-(c_{\rm em}/c_{\rm m})}$.

They conjectured furthermore that the velocity eigen state of massless particle could be different from the limiting velocity $c_{\rm m}$. For neutrinos, if the flavor eigen state and the velocity eigen state is not identical, the neutrino oscillation would happen.

(c)Eigen State of Velocity$^{7,9,10)}$

As seen in the above subsection (b), the introduction of plural limitting velocities violates in general the invariance of the total Lagrangian under the Lorentz transformation. But, if their differences are as small as like 10^{-22}, the effect of the violation reveals itself only for high energy such as $\gamma \sim 10^{11}$.

In relation to the neutrino oscillation, Coleman and Glashow$^{10)}$ introduced an interesting idea of "velocity eigen state", that postulates the limitting velocity takes eigen values, those are almost degenerate but slightly split into different values. They even assume that this velocity eigen states may be not diagonal to the flavor eigen state of neutrinos. Then, due to this non-diagonal mixing of states, the neutrino oscillation could be explained even if the neutino mass is zero.

Their idea can be generalize into all kinds of particles and they have shown that this violation of the Lorentz invariance does not disturb the renormalizability of the quantum gauge field theory.$^{7)}$ However, this violation will affect to the CPT-theorem and the CP-violation problem must be carefully checked, including the precision experiment of atomic physics.

The application of this idea to the GZK-cutoff has been explicitely discussed in the paper.$^{9)}$ Without a conflict with the proved facts, the GZK-cutoff could be modified not to occure.

(d) Energy dependent light velocity[11)]

If we modify the conventional relation of $c_0^2\mathbf{p}^2 = E^2$ as

$$c_0^2\mathbf{p}^2 \approx E^2[1 + f(E)]$$

,where E is the energy in the S_0 frame. Since the modification might be due to an effect of Quantum gravity, $f(E)$ term would dominate in the Planck energy E_{Pl} and, in the low energy limit, it will take a form of $f(E) \approx \zeta(E/E_{Pl})$. Then the velocity becomes

$$c = \frac{\partial E}{\partial p} \approx c_0(1 - \zeta\frac{E}{E_{Pl}})$$

Combining the stability argument of high energy photons in the above (b), the requirement to explain observed TeV gamma-ray from astronomically remote objects can derive the constraint for $|1 - (c_{\rm em}/c_{\rm m})|$.

Interests on the photon mass has revived in various contexts recently. In case of finite mass, the four vector potential itself has a physical meaning in different from the conventional gauge-potential. Then it might be paved the all space in our universe and might work to provide the universal four vector.

(e) Energy or Velocity?

According to the recent paradigm of the unification between matter and spacetime, the new physics is expected at the Planck energy or Planck length. However, in the phenomenological consideration, this conviction is too narrow. Then it will be too narrow to expect the violation of the Lorentz invariance only in the area of Quantum Garvity.

This consideration invokes a question which of energy and velocity is more critical to real cause of the violation. For examples, the neutrino mass could be the order of 10^{-4}eV and the Lorentz factor might be as large as $\gamma \sim 10^{16}$ for 1TeV neutrino. Then, is somthing strange for 1TeV neutrino? Would be no! But this does not mean that the violation would not occure below $\gamma \sim 10^{16}$. To see the violation, we must see a behavior in the wide energy region including the transient point.

The Lorentz factor γ does not paly any important role in the quantum gravity. γ is concerned with the symmetry rather than the dynamics. Then one should seek another new horizen beside quantum gravity.

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