Extended Lorentz code of a superluminal particle

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While the OPERA experimental scrutiny is ongoing in the community, in the present article we construct a toy model of extended Lorentz code (ELC) of the uniform motion, which will be a well established consistent and unique theoretical framework to explain the apparent violations of the standard Lorentz code (SLC), the possible manifestations of which arise in a similar way in all particle sectors. We argue that in the ELC-framework the propagation of the superluminal particle, which implies the modified dispersion relation, could be consistent with causality. Furthermore, in this framework, we give a justification of forbiddance of Vavilov-Cherenkov (VC)-radiation/or analog processes in vacuum. To be consistent with the SN1987A and OPERA data, we identify the neutrinos from SN1987A and the light as so-called 1-th type particles carrying the individual Lorentz motion code with the velocity of light $c_1 \equiv c$ in vacuum as maximum attainable velocity for all the 1-th type particles. Thereby, we treat superluminal muon neutrinos as so-called 2-nd type particles carrying the individual Lorentz motion code with the velocity $c_2$ as maximum attainable velocity for all the 2-nd type particles. For the muon neutrinos mean energy $E_{\nu_\mu} = 17.5$ GeV, claimed velocity $(v_{\nu_\mu} - c)/c = 2.48 \times 10^{-3}$, and expected finite rest mass $m_0 \approx 1$ eV/c$^2$, we obtain then $c_2/c \approx 17.5 \times 10^9$.

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I. INTRODUCTION

The special relativity (SR) encodes Lorentz symmetry as a particular solution, so-called SLC, to make the interval defined in four-dimensional Minkowski spacetime an invariant for the transformation. This has as its crucial ingredient the universal maximal velocity of light in vacuum - the limiting velocity in Nature, remaining such for all the particles and in all inertial frames of reference. Earlier studies of the neutrinos from the supernova SN1987a, which is in the Large Magellanic Cloud at 51 kiloparsec from Earth, bound scenarios of modification of neutrino velocities. Due to the huge distance of the source of the neutrinos, any small effect would therefore be largely amplified by the long time of flight. These measurements set a stringent limit of $(v_{\nu_\mu} - c)/c < 2 \times 10^{-9}$ for tens of MeV electron neutrinos [4]. Consequently, the MINOS collaboration [2] (with 735 km baseline and a broad neutrino energy spectrum peaked around 3 GeV) claimed the result $\beta_{\nu_\mu} - 1 = (5.1 \pm 3.9) \times 10^{-5}$, $\beta_{\nu_\mu} = v_{\nu_\mu}/c$, which agrees at less than 1.4$\sigma$ with the speed of light. So it does not provide a strong evidence in favour of SLC violating effects. However, the OPERA collaboration has claimed instead a more precise result [3], which corresponds to a 6$\sigma$ effect for super-luminal propagation for muonic neutrinos, thus confirming the MINOS results. The data released are made of 16111 events detected in OPERA and correspond to about $10^{30}$ protons on target collected during the 2009, 2010 and 2011 CNGS runs. The energetic muonic neutrinos $\nu_{\mu}$, mainly produced in the decay, $\pi^\pm \rightarrow \mu^\pm + \nu_{\mu}(\overline{\nu}_{\mu})$, cross the Earth’s crust with mean energy of 17.5 GeV about 730 km from CERN to the Gran Sasso at a speed exceeding that of light $(v_{\nu_\mu} - c)/c = (2.48 \pm 0.28(\text{stat.}) \pm 0.30(\text{sys.})) \times 10^{-5}$ a significance of six standard deviations. Shortly after this a second test is also performed by using a beam with a short-bunch time - structure allowing to measure the neutrino time of flight at the single interaction level. The new analysis show consistent result with that at the first version. We deliberately forebear from any presumption of exotic hypothetical tachyonic or a pseudo-tachyonic behavior of superluminal neutrinos, which seems nowhere near true even though if one applies the Magorana’s [4] additional solution of Dirac equation with imaginary mass term. In this, a possible option for a causal description is to allow tachyons to be incorporated in the framework of absolute simultaneity for space-time events [5], or, equivalently, the existence of a preferred reference frame but, by its very existence, breaks Lorentz invariance. The dispersion relation for tachyons, $E^2 - c^2 p^2 = -k^2 c^4$, leads to the large tachyonic mass of the OPERA muon neutrino: $k \approx 120$ MeV/c$^2$. This result is entirely incompatible with the last quoted one determined from the kinematics of the pion decay at rest: $\pi \rightarrow \mu + \nu_\mu$, [6], which yielded $m_{\pi}^2 c^4 = -0.016 \pm 0.023$ MeV$^2$ [7]. Furthermore, a tachyon may decay in number of exotic channels and so tachyonic beam would be distorted upon its arrival at the Gran Sasso. However, without ever referring to tachyonic physics, a hint to superluminal neutrino propagation, if correct, already clashes with the SLC of uniform motion of a particle at least for the following two crucial reasons.

(1) A standard SR dispersion relation breaks down as the Lorentz factor $\gamma = 1/\sqrt{1 - \beta^2}$ becomes imaginary number and the total energy cannot be positive definite.

(2) A superluminal propagation violates the causality, so the CNGS beam may become GSCN when seen from...
a sufficiently boosted reference frame.

We begin by visualization of some properties of the violation of the causality principle in the context of OPERA experiment. Suppose that the measurement for both neutrinos and light involves two points on the X axis of the reference frame S of the Earth. That is, the superluminal muon neutrino beam is produced at the point A - by accelerating protons to 400 GeV/c with the CERN Super Proton Synchrotron (SPS), travels to the point B - OPERA detector at Gran Sasso Laboratory, with the velocity \( v_{\nu} \) and at B produces some observable phenomenon, namely an identification of the \( \tau \)-lepton created by its charged current (CC) interaction, which is the signature of direct appearance mode in the \( \nu_\mu \to \nu_\tau \) channel. The starting of the neutrino travel at A and the resulting phenomenon at B thus are being connected by the relation of cause and effect. The time elapsing between the cause and its effect as measured in OPERA experiment is

\[
\Delta t = t_B - t_A = \frac{x_B - x_A}{v_{\nu}} = \frac{720\text{km}}{v_{\nu}} \approx 987.8\text{ns},
\]

where \( x_A \) and \( x_B \) are the coordinates of the two points A and B. Now in another system \( S' \), which is chosen so that the Cartesian axes \( OX \) and \( O'X' \) lie along the same line, also denote \((x, y, z)\) the resulting phenomenon at B thus are being connected by the relation of cause and effect. The time elapsing between cause and effect would evidently be

\[
\Delta t' = t'_B - t'_A = \frac{t_B - y_B}{\sqrt{1 - x'^2}} - \frac{t_A - y_A}{\sqrt{1 - x'^2}} = \frac{1 - \frac{xV}{c^2}}{\sqrt{1 - x'^2}} \Delta t.
\]

Suppose

\[
V = c(1 - 1.48 \times 10^{-5}),
\]

then \( \frac{xV}{c^2} \) would be greater than unity

\[
\frac{xV}{c^2} \approx 1 + 1 \times 10^{-5},
\]

and hence, \( \Delta t' \) becomes negative

\[
\Delta t' \approx \frac{-1 \times 10^{-5}}{\sqrt{1 - (1 - 1.48 \times 10^{-5})^2}} \Delta t \approx -1.82 < 0.
\]

In other words, for an observer in system \( S' \) the effect which occurs at GS would precede in time its cause which originates at CERN. It is extremely hard to envisage a consistent theory having such a logical impossibility. It is not excluded, however, that the OPERA measurement report will eventually fail. Waiting for further developments, see e.g. [8–47], nevertheless it is extremely challenging to explain SLC apparent violations in a consistent theoretical framework. We have proposed what is perhaps the minimal change in this regard. We develop on the ELC of uniform motion which is a well established consistent and unique theoretical framework to explain SLC apparent violations. The possible manifestations of the latter arise in a similar way in all particle sectors. It should be stressed that a discovery of a superluminal particles would not invalidate the Einstein’s theory, as is notoriously claimed, but suggest an extension in the superluminal sector. Since in the framework of ELC a charged superluminal particle is allowed to propagate in vacuum with a constant speed \( v > c \) higher than that of light, then at first sight it seems that this particle will radiate VC-radiation until it is no longer superluminal. So, this and analog processes are absent below a characteristic energy and turn on abruptly once the threshold energy is reached and, therefore, beam of superluminal particles would be profoundly depleted as they propagate due to energy losses via the VC-radiation/or analog processes. But as we will see, in the ELC-framework the VC-radiation/or analog processes of the superluminal particle propagating in vacuum are forbidden. We will proceed according to the following structure. In the next section, we explain our idea of what is the individual Lorentz motion code of a particle and lay a foundation of the ELC-framework. In this, a modification of the dispersion relation for superluminal particle is given. The causality principle for a superluminal propagation is dealt with in section 3, in particular it was studied in the context of OPERA experiment. In section 4, in the ELC-framework, we give a justification of forbiddance of VC-radiation/or analog processes of a superluminal particle propagating in vacuum. The concluding remarks are presented in section 5.

II. THE ELC-FRAMEWORK

The Lorentz transport equations are so constructed as to make the interval between the infinitely close to each other two events defined in Minkowski spacetime

\[
ds^2 = (dx^0)^2 - (dx^1)^2 - (dx^2)^2 - (dx^3)^2 = \text{inv},
\]

an invariant for the transformation, and from the equality of the infinitesimal intervals there follows the equality of the square of the "length" of the radius four-vectors. Consider again two systems S and \( S' \) in relative motion. A system \( S' \) is chosen so that the Cartesian axes \( OX \) and \( O'X' \) lie along the same line, also denote \((x^1, x^2, x^3) \equiv (x, y, z)\). The Lorentz transformation always retains its general form

\[
x'^0 = x^0 c \beta + x^1 \beta, \quad x' = x c \beta + x^0 \beta, \quad y' = y, \quad z' = z, \quad c \beta = \sqrt{1 - \frac{y^2}{c^2}}, \quad \beta = \frac{V}{c}.
\]

The standard SR theory encodes Lorentz symmetry as a particular solution (SLC-framework) to \([7]\):

\[
\text{namely introducing a notion of 'time', for all inertial frames of reference \( S, S', S'',... \), we have then SLC-relations: } x^0 = ct, \quad x'^0 = ct', \quad x'^0 = ct'',... , \quad \text{agreed with } [7].
\]

Here, for further simplification we suppose that the starting-point for 'time' measurements in the two systems is taken so that \( t \) and \( t' \) are equal to zero when the two origins O and O’ are in coincidence. The SLC, in fact, is Einstein’s postulate that the velocity of light \( c \) in free space
appears the same to all observers regardless the relative motion of the source of light and the observer. Treating the SLC entirely as properties of four-dimensional Minkowski space, it implies the velocity of light (c) to be universal maximum attainable velocity of a material body found in this space. Even though, if for a moment we take the light as a not interacting (unobservable) hidden physical state, nevertheless the SLC will hold and, as before, the velocity of light (c) will be maximum attainable velocity for all other particles. However, it is possible to preserve Lorentz covariance in a theory also with a formal general solution to (6), which can be obtained if the 'time' at which event occurs is extended by allowing an extra dependence on the 'different type' readings \( t_i \) (\( i = 1, 2, ... \)), which satisfy for all inertial frames of reference \( S, S', S'' \),..., so-called ELC-relations:

\[
\begin{align*}
 x'^0 & \equiv c_1 t_1 = \cdots = c_i t_i = \cdots , \\
 x'^j & \equiv c_1 t'_1 = \cdots = c_i t'_i = \cdots , \\
 \vdots & \quad \vdots
\end{align*}
\]

agreed with (7), where \( c_1 \equiv c \) is the speed of light in vacuum, and \( c_i > c_1 \) (\( i = 2, 3, ... \)) are speeds of the additional 'light-like' states, higher than that of light. These missing ingredients are the shortcoming of ELC-framework, which will be motivated elsewhere. Phenomenologically such 'light-like' states can be easily accommodated if for now to think of them as being the hidden, or it may very well be that unobserved yet, states that constitute the ELC. This assumption has the important consequence that it may not be too unreasonable to link the existence of a different type readings \( t_i \) to the existence of a different type of particles. This will call for a complete reconsideration of our ideas of Lorentz motion code, to be now referred to as the individual code of a particle - as its intrinsic property. This observation allows us to lay forth a toy model of the ELC, at which SLC violating new physics appears. That is to say, the \( i \)-th type particle in Minkowski space carries an individual Lorentz motion code with its own maximum attainable velocity \( c_i \) ('its own velocity of light-like state'). The clock reading \( t_i \) can be used for the \( i \)-th type particle, the velocity of which reads \( v_i = x/t_i = c_i x/x^0 \), so \( \beta = v_i/c_i = \cdots = v/c = x/x^0 \). If \( v_i = c_i \) then \( x_i = c_1 \), and the proper time of 'light-like' states are described by the null vectors \( ds^2 = \cdots = 0 \). The extended Lorentz transformation equations for given \( i \)-th and \( j \)-th type clock readings can be written then in the form

\[
\begin{align*}
 x' & = \gamma (x - vt), \\
 t' & = \gamma \frac{c_i}{c_j} (t_j - \frac{v_j}{c_j} x), \\
 y' & = y, \quad z' = z.
\end{align*}
\]

Hence, like the standard SR theory, regardless the type of clock, a metre stick travelling with system S measures shorter in the same ratio, when the simultaneous positions of its ends are observed in the other system \( S' \): \( dx' = dx/\gamma \). Furthermore, a time interval \( dt_i \) specified by the \( i \)-th type readings, which occur at the same point in system \( S \) (\( dx = 0 \)), will be specified with the \( j \)-th type readings of system \( S' \) as \( dt'_j = \gamma (c_i/c_j) dt_i \). Consequently, the modified transformation equation for velocity is

\[
v_i = \frac{c_i - v_j/c_j}{1 + \frac{c_i c_j}{c_j^2}}.
\]

Here we have called attention to the fact that the mere composition of velocities which are not themselves greater than that of \( c_i \) will never lead to a speed that is greater than that of \( c_i \). Inevitably in the ELC-framework a specific task is arisen then to distinguish the type of particles. This evidently cannot be done when the velocity ranges of different type particles intersect. To reconcile this situation, we note that, according to (5), we may freely interchange the types of particles in the intersection. Therefore, we adopt following convention. With no loss of generality, we may re-arrange a general solution that the particles with velocities \( v_1 < c_1 \), regardless their type, will be treated as the 1-th type particles and, thus, a common clock reading for them and light will be set as \( t_1 \). This part of a formalism is completely equivalent to the SLC-framework. Successively, the particles, other than 'light-like' ones, with velocities in the range \( c_{i-1} \leq v_i < c_i \), regardless their type, will be treated as the \( i \)-th type particles and, thus, a common clock reading for them and 'light-like' state \( (i) \) will be set as \( t_i \). The invariant momentum

\[
\begin{align*}
 p_i^2 & = p_{\mu i} p_{\mu i} = \left( \frac{E_i}{c_i} \right)^2 - \vec{p}_i^2 = m_i^2 c_i^2, \\
 p_1^2 & = p_{\mu 1} p_{\mu 1} = \left( \frac{E_1}{c_1} \right)^2 - \vec{p}_1^2 = m_1^2 c_1^2,
\end{align*}
\]

introduces a modified dispersion relation for \( i \)-th type particle:

\[
E_i^2 = p_i^2 c_i^2 + m_0^2 c_i^2 = p_i^2 c_i^2 + m_0^2 c_i^2, \quad \text{for} \quad i = 2, 3, ..., \quad \text{and} \quad \vec{p}_i = m_i \vec{v}_i = \gamma m_0 \vec{v}_i \text{ is the momentum}. \quad \text{The relation (13) modifies the well-known Einstein's equation that energy E always has immediately associated with it a positive mass} \quad m_i = \gamma m_0, \text{ when moving with the velocity} \quad \vec{v}_i. \quad \text{Having set the theoretical background, we now turn to discuss some consequences for the superluminal propagation of particles. The next sections are devoted mainly to these questions.}

### III. THE CAUSALITY PRINCIPLE FOR A SUPERLUMINAL PARTICLE

In the ELC-framework of uniform motion, the time elapsing between the cause and its effect as measured for the \( i \)-th type superluminal particle is

\[
\Delta t_i = t_{iB} - t_{iA} = \frac{x_{B} - x_{A}}{v_i}.
\]
In another system S’, which is chosen as before and has the arbitrary velocity \( V = V_j \) with respect to S, the time elapsing between cause and effect would be
\[
\Delta t_i' = \frac{1 - \frac{V}{c^2}}{\sqrt{1 - \frac{V}{c^2}}} \Delta t_i \geq 0, \tag{15}
\]
where according to (9) \( t_{iB} = (c_j/c_i)t_{iB} \) and \( t_{iA} = (c_j/c_i)t_{iA} \). That is, the ELC-framework recovers the causality for a superluminal propagation, so the starting of the superluminal impulse at A and the resulting phenomenon at B are being connected by the relation of cause and effect in arbitrary inertial frames. This completes the theoretical discussion and we now turn to the SN1987A and OPERA experimental inputs. To reconcile these data, we identify the neutrinos from SN1987A and the light as the 1-th type particles, and the muon neutrinos as the 2-nd type superluminal particles. While, as discussed in the previous section, for the muon neutrinos mean energy \( E_{\nu_2} = 17.5 \text{ GeV} \) and expected finite rest mass \( m_{01} \approx 1 \text{eV} / \sqrt{c_1^2} \) (\( c_1 \equiv c \)), the maximum attainable velocity \( c_2 \) for all the 2-nd type particles can be obtained as
\[
c_2 = \frac{c_1 E_{\nu_2}}{m_{01} c_1^2} = c_1 \frac{E_{\nu_2}}{m_{01} c_1^2} \sqrt{1 - \frac{\omega_2^2}{c^2}} \approx 17.5 \times 10^3 c. \tag{16}
\]

IV. A FORBIDDANCE OF VC-RADIATION/OR ANALOG PROCESSES IN VACUUM

Assuming that the Lorentz invariance is violated perturbatively in the context of conventional quantum field theory \[9, 33, 34, 35, 50\], this can induce the muon neutrino radiative decay \( (\nu_\mu \rightarrow \nu_\mu + \gamma) \) and the three body decay - for example, the Z-strahlung radiation \( (\nu_\mu \rightarrow \nu_\mu + Z \rightarrow \nu_\mu + e^- + e^+) \), otherwise forbidden but now kinematically permitted, being the analog to VC-radiation \[11, 47\]. Such processes will lead to the fast energy loss of neutrinos once the threshold is reached. This implies that the Lorentz non-invariant contribution added a shift in the momentum, which will result in a shift in the maximum attainable velocity of the particle from the velocity of light \( c \), which remains the maximum attainable velocity for all other particles except the muon neutrino. However, the ELC-framework evidently forbids VC-radiation/or analog processes in vacuum in a similar way in all particle sectors. Actually, in this framework we have to set, for example, \( k_1 = (\frac{x_1}{z_1}, k_1) \) for the 1-th type \( \gamma_1 \) photon, provided \( k_1^2 = \bar{\epsilon}_1 \frac{E_1}{c} \), and \( p_2 = (\frac{x_2}{z_2}, p_2) \) for the 2-nd type superluminal particle. Then the process \((l_2 \rightarrow l_2 + \gamma_1)\) becomes kinematically permitted if and only if
\[
k_1 p_2 = \frac{\omega_1 E_{\nu_2}}{c^2} \left( 1 - \bar{\epsilon}_1 \frac{x_1}{z_1} \right) = 0, \tag{17}
\]
which yields \( \omega = 0 \) because of \( \left( 1 - \bar{\epsilon}_1 \frac{x_1}{z_1} \right) \neq 0 \). So in the case at hand, the VC-radiation/or analog processes are forbidden. This evades constraints due to VC-like processes since the superluminal neutrino \( \nu_{\mu 2} \) does not actually travel faster than the speed \( c_2 \), and that allows the arrival at the Gran Sasso of superluminal neutrinos \( \nu_{\mu 2} \) with the velocity claimed by OPERA of any specific energy, without having lost of their energies. In what follows, in ELC-framework we discuss the VC-radiation of the charged superluminal particle propagating in vacuum with a constant speed \( v_2 > c_1 \) higher than that of light. Recall that, a charged particle \( (e \neq 0) \) moving in a constant isotropic and non-magnetic medium with a constant velocity higher than velocity of light in this medium is allowed to radiate, so-called Vavilov-Cherenkov radiation. The energy loss per frequency is
\[
dF = -d\omega \frac{\omega^2}{2\pi} \sum_\omega (\frac{1}{\omega_2} - \frac{1}{\omega c^2}) \int \frac{d\zeta}{\zeta}, \tag{18}
\]
where the direction of the velocity \( \vec{v} \) is chosen to be \( x- \)direction: \( k_\perp = k \cos \theta = \omega / v \), \( k = n \omega / c \) is the wave number \( n = \sqrt{\varepsilon} \) is the real refractive index, \( \varepsilon \) is the permittivity. The summation is over terms with \( \omega = \pm |\omega| \), and a variable
\[
\zeta = q^2 - \omega^2 \left( \frac{1}{c^2} - \frac{1}{v^2} \right) \tag{19}
\]
is introduced, provided \( q = \sqrt{k_\perp^2 + k^2} \). The integrand in (18) is strongly peaked near the singular point \( \zeta = 0 \), for which \( q^2 + k_\perp^2 = k^2 \). Using standard technique, the formula (18) can be easily further transformed to be applicable in ELC-framework for the charged superluminal particle of 2-nd type propagating in vacuum (i.e. if \( \varepsilon = 1 \)) with a constant speed \( v_2 \) higher than that of light \( (c_1 \leq v_2 < c_2) \):
\[
dF = -d\omega \frac{\omega^2}{2\pi} \sum_\omega (\frac{1}{\omega_2} - \frac{1}{\omega c^2}) \int \frac{d\zeta}{\zeta}, \tag{20}
\]
and, respectively, (19) becomes
\[
\zeta = q^2 - \omega^2 \left( \frac{1}{c^2} - \frac{1}{v_2^2} \right), \tag{21}
\]
where \( q_1 = \sqrt{k_{x1}^2 + k_{z1}^2} \), \( q_2^2 + k_{x2}^2 = k_1^2 = \omega^2 / c_1^2 \), and now \( k_{x1} v_2 = \omega \). We have then
\[
\zeta = \frac{\omega^2}{c_1^2} \left( \frac{c_1^2}{v_2^2 \cos^2 \theta} - 1 \right) \neq 0, \tag{22}
\]
because of \( v_2 < c_2 \), and that the integral (20) is zero, since the integrand has no poles. Hence, as expected, the VC-radiation of a charged superluminal particle as it propagates in vacuum is forbidden.

V. CONCLUDING REMARKS

To summarize, we have pointed out that if there were some superluminal particles which indeed violet the SLC, the ELC will be a well established consistent and unique
theoretical framework to explain these apparent violations, the possible manifestations of which arise in a similar way in all particle sectors. We drastically change our ideas of Lorentz motion code, treating it as an individual code of a particle - as its intrinsic property. The shortcoming of the ELC-framework, of course, are the missing ingredients of the heuristic 'light-like' states other than that of light, which will be motivated elsewhere. We for now think of them as being the hidden, or it may very well be that of unobserved yet, states that constitute the ELC. The ELC-framework recovers the dispersion relation and the causality for a superluminal propagation, as well as forbids VC-radiation/or analog processes of a superluminal particle propagating in vacuum. In the context of the OPERA experiment, we treat superluminal muon neutrinos as 2-nd type particles carrying the individual Lorentz motion code with the velocity \( c_2 \) as maximum attainable velocity for all the 2-nd type particles. We obtain then \( c_2 \approx v_2(1 + 1.65 \times 10^{-21}) \).

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