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Superluminal speed of Neutrinos observed at the OPERA experiment

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Abstract: *The OPERA neutrino experiment has measured the velocity of neutrinos and it revealed that the neutrino speed exceeds the light speed. In this article, this superluminal phenomenon can be possible due to the quantum tunneling through the light barrier, which predicts the theoretical value similar to the experimental result for light particles compared with electrons.*

Keywords: *OPERA neutrino experiment, neutrino, superluminal speed, quantum、 tunneling effect.*

Introduction

Recently, a group of physicists have been working to measure the neutrinos generated from a particle accelerator at CERN. This group discovered neutrinos arriving faster than would have been expected and they appear to be traveling faster than the speed of light itself, but they draw no definitive conclusions (McLaughlin, 2011). In the experiment, neutrinos are generated at the Super Proton Synchrotron (SPS) particle accelerator at the CERN LHC complex in Geneva and further accelerated down a 1 km beam line toward the Gran Sasso National Laboratory in Italy. At Gran Sasso, a detector instrument called OPERA measures the neutrinos. The distance from CERN to Gran Sasso is 732 km straight through the Earth, traveling up to 11.4 km below the Earth's surface.

Figure 1: Did OPERA detect the superluminal speed of neutrinos?

The speed of neutrinos is measured and compared to the speed of light by subtracting the expected time for light to travel the distance from the time for the neutrinos to travel the same distance. One would normally expect this to be zero for neutrinos traveling at the speed of light or negative for any value below the speed of light. The case presented in the article shows a positive value of 60.7 nanoseconds with statistical and systematic errors providing not nearly enough potential difference to account for the positive value.
The conclusion that can be drawn from this article is that a group of experimenters found an unexpected result using some of the most amazing and precise instruments and techniques ever created. No matter what is found to be the actual cause of this 60.7 nanosecond variation, the conclusion you can draw is that it is an amazing time in history where such measurements can be made and an exciting time to be a practitioner or admirer of science (Adam and Agafonova, 2011). The rest mass of neutrinos has been assumed to be zero. However recent measurements on electron neutrinos suggest that they might have an imaginary rest mass (Holzschuh et al., 1992; Weinheimer et al., 1993; Kawakami et al., 1991; Robertson et al., 1991; Stoeffl and Decman, 1995). This means that they are superluminal particles, which were named tachyons by G.Feinberg (1967). The purpose of this paper is to examine the possibility of electron neutrinos being emitted from the atomic nucleus as a tachyon.

Possibility of Neutrinos Detected as Tachyons

From the bosonic string world-sheet action given by

$$S=\frac{1}{4\pi\alpha'}\int d^2\sigma\sqrt{-g}\,g^{ab}\partial_a X^{\mu}\partial_b X_{\mu} \ , \qquad (1)$$

The spectrum of bosonic strings contains a tachyonic mode for open strings shown as (Szabo, 2004)

$$m^2=-\frac{1}{\alpha'} \ , \ 0 \ , \frac{1}{\alpha'} \ , \frac{2}{\alpha'}, \cdots \ , \qquad (2)$$

Which allows the existence of negative energy, that leads to the instability of the vacuum. This means that the tachyon is an unstable particle, which is allowed to appear for a short period of time in empty space. Musha, one of authors, presented the idea in his article that highly accelerated particles has the possibility to penetrate through the light barrier in a finite length of time (Musha, 1998).
According to his idea, he has shown that there is a possibility of virtual particles created temporarily out from ZPF field as tachyons by quantum tunneling effect as shown in the following.
From the wave function taking account of the special relativity for the particle given by

$$i\hbar\frac{\partial\psi}{\partial t}=H\psi \ , \qquad (3)$$

Where H is a Hamiltonian given by $H=\sqrt{p^2c^2+m^2c^4}$ (p :momentum of the particle, m :effective mass) and ψ is a wave function for the particle, the following equation can be obtained for the accelerating particle;

$$i\hbar\frac{\partial\psi}{\partial t}=c\sqrt{p^2+m_o^2c^2}\,\psi \ , \qquad (4)$$

Then the particle under acceleration becomes

$$\frac{\partial \psi}{\partial p} = i \frac{c}{m_o \alpha \hbar} \sqrt{p^2 + m_o^2 c^2} \psi \, , \quad (5)$$

by using the proper acceleration α given by (Jyukov, 1961)

$$p = m_o (t - t_o) \, , \quad (6)$$

Where p is a momentum of the particle.

According to the uncertainity principle, the proper acceleration of the particle moving inside the atomic nucleus can be roughly estimated as

$$\alpha = \frac{1}{m_o} \frac{\Delta p}{\Delta t} \approx \frac{c\hbar}{m_o L^2} \, , \quad (7)$$

Where L is a size of the atomic nucleus.

Hence the penetration probability through the light barrier of the highly accelerated particle can be estimated by

$$T \approx |\psi_{II}|^2 / |\psi_I|^2 = \exp\left[-\frac{\pi}{2} \frac{m_o^2 c^2 L^2}{\hbar^2} \right] , \quad (8)$$

according to the WKB approximation.

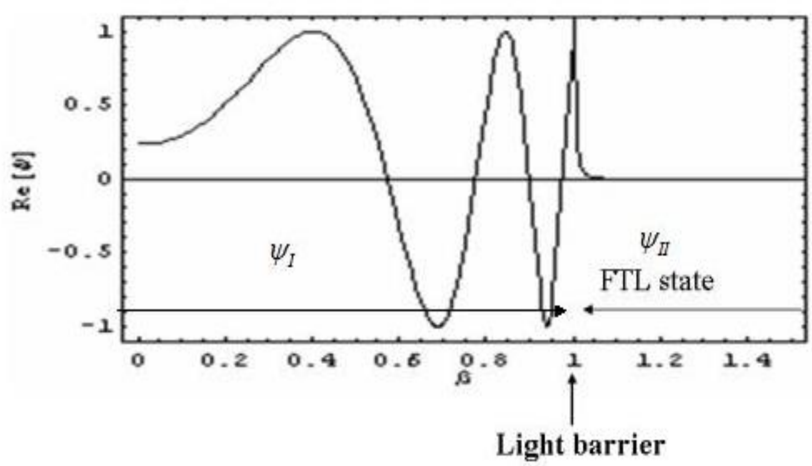

Figure 2: Wave function of a tunneling particle through the light barrier

Analysis of the Experimental Result

By the uncertainty principle of the momentum, the velocity of the particle created inside the quantum region, which size is L, can be given from the relation shown as

$$p = \frac{m_o v}{\sqrt{1 - v^2 / c^2}} \, , \quad (9)$$

from which, we have

$$v \approx c - \frac{c}{2}\frac{m_0^2 c^2 L^2}{h^2} \ , \tag{10}$$

for the light particle which satisfies $mcL/h << 1$.

$$p_* = \frac{m_* v}{\sqrt{v_*^2/c^2 - 1}} \ , \tag{11}$$

$$v_* \approx c + \frac{c}{2}\frac{m_*^2 c^2 L^2}{h^2} \ , \tag{12}$$

As stated in the previous section, the tachyons is an unstable particle, which is allowed to appear for a short period of time in empty space, the traveling distance of neutrinos in a FTL state can be estimated from the uncertainty principle as follows; According to M. Park and Y. Park (1996), the uncertainty relation for the superluminal particle can be given by

$$\Delta p \cdot \Delta t \approx \frac{\hbar}{v - v'} \ , \tag{13}$$

where v and v' are the velocities of a superluminal particle before and after the measurement.

$$\Delta p = \left| p_* - p \right| = \frac{m_0 c(v_* - v)}{\sqrt{c^2 - v^2}} = \frac{m_0^2 c^2 L}{h} \ , \tag{14}$$

which can be derived from

$$\Delta p \Delta t \approx h \Big/ \left(\frac{m_0^2 c^3 L^2}{h^2} \right) = \frac{h^3}{m_0^2 c^3 L^2} \ , \tag{15}$$

From which, we have

$$\Delta t \approx \frac{h^4}{m_0^4 c^5 L^3} \ , \tag{16}$$

the distance of neutrinos traveling in a FTL state becomes

$$\Delta x = v_* \Delta t \approx \frac{h^4}{m_0^4 c^4 L^3} \ . \tag{17}$$

From them, it is seen that the light particle emitted from the nucleus has the possibility traveling as a tachyon temporarily according to the uncertainty principle.

Nevertheless, it should be noted that in the classical formulation (generally named "classical theory of tachyons") the proper tachyon mass appearing the dynamical equations is assumed to have an imaginary value $m_o = im_*$ meaning that tachyons couldn't be experimentally revealed. This is one of the most important difficulty with such commonly considered description of such hypothetical particles. Nevertheless, in a recent publication (Caligiuri, 2019), L.M. Caligiuri show that, by reformulation Einstein's Special Theory of Relativity in the space-like region, it is possible to describe tachyons as real rest-mass particles. In particular this very important result can be achieved by introducing a "space-like" metric and a physical "tachyonic reference frame" (TRF) in which it holds. A TRF is defined as the set of all the word – lines constituted by a succession of "superluminal" events related by the following metric

$$dS^2 = G_{\mu\nu} dX^\mu dX^\nu \quad \mu,\nu = 1,2,3,4 \ , \qquad (18)$$

that is a real function of the coordinates X^μ defined in a TRF and such as $dS^2 > 0$.

The metric (18) has the signature $(-,+,+,+)$ and defines a superluminal manifold $\tilde{E}_4(dS^2)$ as a pseudo-euclidean space whose metric tensor is given by:

$$\left[G_{\mu\nu}\right] = \begin{bmatrix} -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} , \qquad (19)$$

in the same way as the (usual) metric

$$ds^2 = g_{\mu\nu} dx^\mu d^\nu \ (\mu,\nu = 1,2,3,4), \qquad (20)$$

with

$$\left[g_{\mu\nu}\right] = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix} , \qquad (21)$$

with the signature $(+,-,-,-)$ defines the subluminal manifold $E_4(ds^2)$ and a usual "ordinary" inertial reference frame.

The metric (19) leads, under very general physical assumptions (Caligiuri, 2019), to the superluminal space-time transformations

$$\begin{cases} X'_3 = \dfrac{\beta X_3 - X_0}{\sqrt{\beta^2 - 1}} \quad X'_0 = \dfrac{\beta X_0 - X_3}{\sqrt{\beta^2 - 1}} \\ X'_1 = X_1 \qquad\qquad X'_2 = X_2 \end{cases} , \qquad (22)$$

By means of (19) we can also calculate the components of the velocity four-vector in a TFR as

$$u^i = \frac{v^i}{c\sqrt{\beta^2 - 1}}; \; u^4 = \frac{1}{\sqrt{\beta^2 - 1}} \; , \tag{23}$$

where $v^i = dX^i / dT$ are the components of three-velocity ($i = 1,2,3$). If we make such an assumption we can characterize the dynamical features of a tachyon by means of a real parameter μ having the dimensions of a mass so that the fundamental equation of tachyon dynamics is written as ($\alpha = 1,2,3,4$)

$$\mu c^2 \frac{\nabla u^\alpha}{dS} = F^\alpha \tag{24}$$

where ∇u^ε designates the absolute differential of u^α, namely

$$\nabla u^\alpha = du^\alpha + \omega_h^\alpha u^h , \tag{25}$$

with

$$\omega_h^\varepsilon = \Gamma_{lh}^\alpha dy^l \tag{26}$$

where Γ_{lh}^α is the Christoffel symbol

$$\Gamma_{lh}^\alpha = \frac{1}{2} g^{\alpha s} \left(\frac{\partial g_{sh}}{\partial x^l} + \frac{\partial g_{ls}}{\partial x^h} + \frac{\partial g_{lh}}{\partial x^s} \right) \tag{27}$$

The four-vector energy-impulse of a tachyonic particle can be then written as ($\alpha = 1,2,3,4$)

$$p^\alpha = \mu c u^\alpha \tag{28}$$

with

$$\tilde{p} = \frac{\mu \beta c}{\sqrt{\beta^2 - 1}}; \; \tilde{E} = \frac{\mu c^2}{\sqrt{\beta^2 - 1}} \tag{29}$$

so we have

$$\tilde{p}^2 c^2 - \tilde{E}^2 = \mu^2 c^4 , \tag{30}$$

that is exactly the same mathematical expression obtained within the classical theory of tachyons that, instead, is based on the unphysical assumption of an imaginary rest mass.

On the contrary we have obtained Eq.(30) directly from the general equation of dynamics of the tachyonic

manifold deduced through the analysis of the mathematical superluminal Lorentz group $\widetilde{L}_{+}^{T}$, the mass of a free tachyon being real.
According to the above discussion the tachyon mass can be described through a real parameter $m_o = \mu$ namely by an experimentally measurable quantity in a suitable reference frame.

Calculation Result for the Muon Neutrino to Verify the Experimental Data

Supposing that the mass of the muon neutrino be less than 170keV, and the size of the quantum region be the size of a Plank length where the neutrino is created from the vacuum, we have $m_0 < 10^{-32}$ kg and $L \approx 1.6\times10^{-35} m$.
Inserting this vale into Eqs.(5), (14) and (15), we have $T \approx 1$, which means that the muon neutrino travels in a FTL state as observed by the experiment.
When we let. $m_0 < 10^{-32}$ kg, we have $\Delta t > 0.0079$sec, and $\Delta X > 2380$km, which are the traveling time and the traveling distance of neutrinos in a superluminal state respectively obtained from Eqs.(16) and (17). The separation between the source at CERN and the OPERA detector at LNGS was 732km as shown in Figure.3. Thus there is a possibility that OPERA detected neutrinos in a superluminal state.
They obtained $(v-c)/c = 2.48 \pm 0.28(stat) \pm 0.30(sys) \times 10^{-5}$ and the MINOS experiment reported a measurement of $(v-c)/c = 5.1 \pm 2.9 \times 10^{-5}$ (Adam and Agafonova, 2011).
Hence it is considered that the muon neutino travels in a superluminal state as confirmed by the OPERA experimental result.

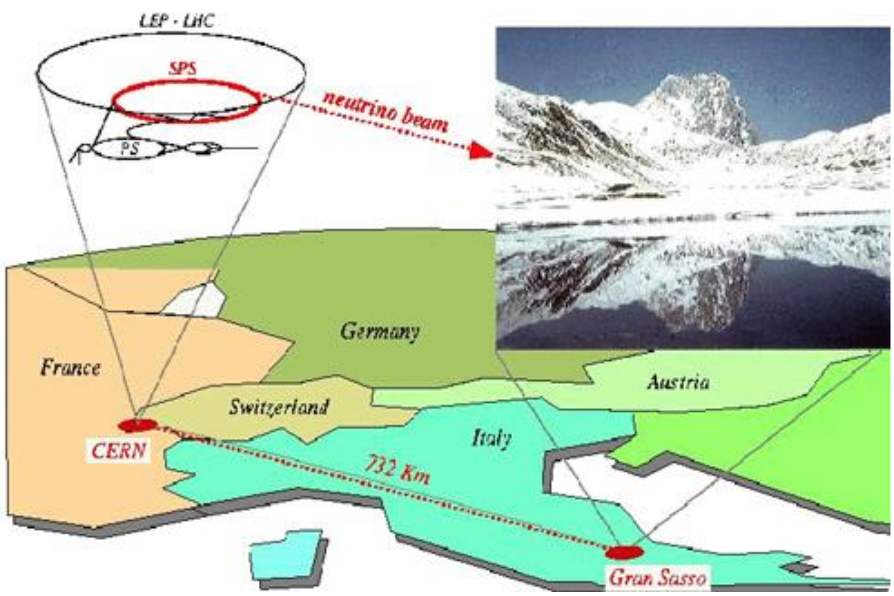

Figure 3: OPERA experiment

Such a superluminal speed was observed in the Universe.
Far away from our galaxy, several of the quasars seem to show two components flying apart at high velocity. In a few cases, the velocity appears to exceed that of light. They leave 3C345 flying apart at apparently 2.5 times the speed of light (Anonymous, 1976).
Apparent superluminal speeds of this kind are in fact being observed. In 1973, in the quasar 3C279 a luminous component was found that apparently moves away from the quasar core at ten times the speed of

light as shown in Figure.4. At the present time, a number of these so called superluminal quasars is known, among them 3C273. From the observation, the jet of this quasar moves away from the quasar core at a rate of about three quarters of a milliarcsecond per year. The redshift of the quasar indicates a distance of about 2.6 billion light years. A path at this distance that extends over three quarters of a milliarcsecond in the sky, is more than nine light years long. Thus, the component appears to traverse 9 light years in the course of a single year. This would make it nine times as fast as light. In addition, the motion that we observe is only the transverse part. There is an additional unobserved velocity component of unknown size in the direction of the line of sight (Unwin et al., 1989).

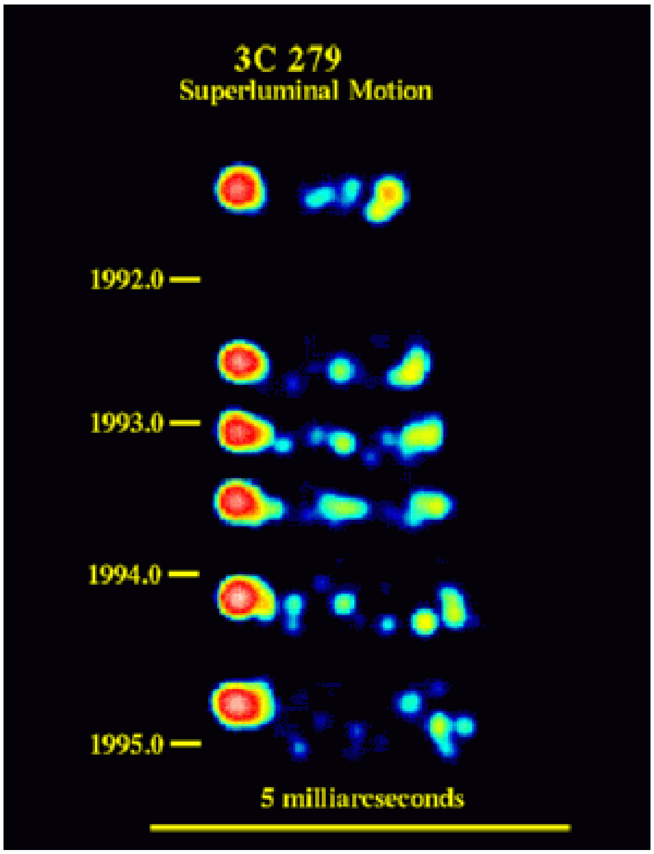

Figure 4: Superluminal motion in quasar 3C279

From the observation of superluminal velocities, they would destroy one of the foundation of modern physics, that is the special relativity theory, and we must reconsider OPERA experimental result which might find superluminal phenomenon.

Conclusion

The possibility that the elementary particles such as neutrinos with small masses compared with electrons can be created as tachyons has been confirmed by the OPERA experimental result.

Yet, OPERA's faster-than-light neutrino data persisted. The next step would be to seek independent confirmation outside of OPERA itself, which is common practice. The Higgs, for example, was observed by both the ATLAS and CMS experiments. But there were no other experiments that could confirm or deny OPERA for at least several years. There was, however, another experiment at the base of Gran Sasso, called the Large Volume Detector (LVD), that could at least check OPERA's timing system. The idea was to make sure the clocks of each experiment were synchronized by comparing the arrival times of cosmic ray muons in their respective detectors.

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