Confronting the Faster-Than-Light Neutrinos?

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Fundamental Theories:

Newtonian Mechanics

Classical Mechanics is not applicable to fast moving particles:
Special Theory of Relativity

Uncertainty Principle at short distances:
Quantum Mechanics

Interactions of Relativistic particles at short distances:
Quantum Field Theory

Newton's Law of gravitation fails for relativistic particles:
General Theory of Relativity

How well do we know Special Theory of Relativity, Quantum Mechanics, General Theory of Relativity (and hence, the Equivalence Principle), CPT theorem, Spin-Statistics theorem ???

Structure of the talk

- Recent experiment on faster-than-light neutrino
- It's implication on Special Theory of Relativity and Lorentz invariance
- Confronting the experiment using phenomenological constraints
- Testing the violation of Lorentz invariance from Cosmic Ray data
- Constraining equivalence principle violation
- The Standard Model and the Higgs scalar
- Cosmology and beyond the standard model

Recent Experiment on faster-than-light neutrino:

A muon neutrino ν_μ beam was produced at CERN, Geneva:

A 400 GeV/c proton beam $\longrightarrow$ charged pions and kaons $\longrightarrow$

$$\pi \longrightarrow \mu + \bar{\nu}_\mu \quad K \longrightarrow \mu + \bar{\nu}_\mu$$

OPERA Collaboration at the Gran Sasso Underground Laboratory (LNGS), detected the ν_μ from CNGS at a distance of 730 kms away.

The arrival time reported by the OPERA collaboration is earlier than expected from luminal speed by a time interval

$$\delta t = (60.7 \pm 6.9_{stat} \pm 7.4_{syst})\ \text{ns.}$$

This implies a superluminal propagation velocity for neutrinos:

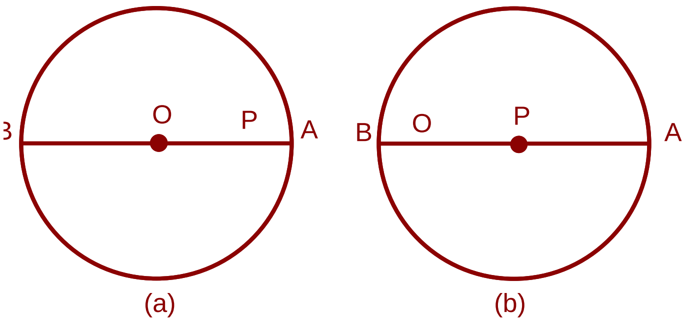
$$\delta c_\nu = \frac{(v_\nu - c)}{c} = (2.48 \pm 0.28_{stat} \pm 0.30_{syst}) \times 10^{-5}$$

for an average energy of 17 GeV.

Special Theory of Relativity:

1. **The principle of relativity:** The laws of physics are not affected by the motion of any inertial reference frames, *i.e.* the frames that are moving with constant velocity with respect to each other.

2. **The principle of invariant light speed:** Speed of light in empty space (c) is constant and same in all inertial frames.



Both the observers at O and P will find that light travelled by a distance c in all directions to the circle in 1 sec. (a) Observer O will find himself at the center of the circle, (b) while observer at P will also find himself at the center of the circle.

Particles with $v > c$ are the Tachyons.

Tachyon:

Consider energy-momentum relationship: $E^2 = \vec{p}^{\,2} c^2 + m^2 c^4$

For $m \ll \vec{p}$, we can express: $E = \vec{p}c + \frac{m^2 c^4}{2\vec{p}c}$

From the Hamilton-Jacobi equation: $v = \frac{dE}{d\vec{p}} = c - \frac{m^2 c^4}{2\vec{p}^{\,2} c}$

$$
\begin{aligned}
\mathit{Ordinary\ massive\ particles:} \quad & m^2 > 0 \Rightarrow v < c \\
\mathit{Light\ and\ other\ massless\ particles} \quad & m^2 = 0 \Rightarrow v = c \\
\mathit{Tachyons} \quad & m^2 < 0 \Rightarrow v > c
\end{aligned}
$$

Tachyons will find light travelling with velocity $-c \Rightarrow t \longrightarrow -t$

If ν_μ s are tachyons, for the OPERA value of $c_{\nu_\mu} = 2.5 \times 10^{-5}$ SN1987A neutrinos would have reached us four years earlier.

Apparently observed faster-than-light neutrinos cannot be Tachyons.

Observed supernovae SN1987A neutrinos implies: $|\delta c_\nu| < 2 \times 10^{-9}$

Lorentz Invariance and OPERA:

Assume energy-momentum is conserved in a particular reference frame

A Lorentz transformation for an observer moving at velocity $\vec{v}$ yields

$$\vec{p} = \gamma\, m\, \vec{v}\,; \quad \text{and} \quad E = \gamma\, m\, c^2\,,$$

where $\gamma = 1/\sqrt{1 - v^2/c^2}$ is the Lorentz factor.

The invariant momentum is defined as $p^2 = p_\mu p^\mu = \left(\frac{E}{c}\right)^2 - |\vec{p}|^2 = m^2 c^2\,,$

so that $E^2 = |\vec{p}|^2 c^2 + m^2 c^4$

For any massive particle we thus require $v < c$, which contradicts OPERA result.

For a muon neutrino with mass around $m \sim 1$ eV and energy $E \sim 17$ GeV

$$(c - v)/c \sim 10^{-20}.$$

Violation of Lorentz Invariance:

Gauge invariant Lorentz non-invariant interaction (Coleman & Glashow)

$$i\,u^\dagger\,\left[D_0 - i(1-\epsilon/2)\vec{\sigma}\cdot\vec{D}\right]\,u\,.$$

The parameter ϵ is a measure of violation of Lorentz invariance.

This implies a modified energy-momentum dispersion relation:

$$p^2c^2 = E^2 - |\vec{p}|^2c^2 = m^2c^4 + \epsilon|\vec{p}|^2c^2\,.$$

In other words, writing the dispersion relation as

$$E^2 = |\vec{p}|^2c_{\nu_\mu}^2 + m_{\nu_\mu}^2c_{\nu_\mu}^4\,.$$

the maximum attainable velocity, and the mass are now modified:

$$c_{\nu_\mu}^2 = (1+\epsilon)c^2 = (1+\epsilon);\quad m_{\nu_\mu} = m/(1+\epsilon)$$

With the new Lorentz factor $\gamma_{\nu_\mu} = 1/\sqrt{1-v^2/c_{\nu_\mu}^2}$, we have

$$E = \gamma_{\nu_\mu}m_{\nu_\mu}c_{\nu_\mu}^2 = \gamma_{\nu_\mu}m \;\text{ with }\; \frac{(c_{\nu_\mu}-v)}{c_{\nu_\mu}} \approx \frac{m^2}{2E^2}\,,\;\text{ for very large } v$$

.

The present result from OPERA gives

$$\frac{(v-c)}{c} = v - 1 = (2.48 \pm 0.28 \pm 0.3) \times 10^{-5}\,.$$

When Lorentz invariance is violated, the Lorentz factor contains

$$\frac{(c_{\nu_\mu} - v)}{c_{\nu_\mu}} \approx \frac{m^2}{2E^2} \approx 10^{-20}\,.$$

Since $c < v < c_{\nu_\mu}$, the present measurement of the ν_μ velocity v becomes consistent with the modified Lorentz factor and the ν_μ remains time-like.

Different particles can have different limiting velocities (c_i), if Lorentz invariance is violated.

If the limiting velocities of the three neutrinos are different, that would lead to neutrino oscillations. Present experimental constraints imply $|c_{\nu_i} - c_{\nu_j}| < 10^{-22}$ for $i \neq j;\ \ i,j = e,\mu,\tau$.

Simplest solution is to assume, $c_{\nu_e} = c_{\nu_\mu} = c_{\nu_\tau} = c_\nu$. OPERA then requires $c_\nu = 2.5 \times 10^{-5}$.

Phenomenological Constraints:

Consider a decay process: $A \longrightarrow B + C$

This is allowed if $M_A > M_B + M_C$.

In case of VLI, one may write effective mass of the particles as $m_X = m_X + \alpha \vec{p}^{\,2}$.

Thus if A is superluminal, the decay condition becomes

$$M_A + \alpha_A \vec{p}_A^{\,2} > M_B + \alpha_B \vec{p}_B^{\,2} + M_C + \alpha_C \vec{p}_C^{\,2}$$

Consider pion decay: $\pi \longrightarrow \mu + \nu_\mu$

If ν_μ is superluminal ($\alpha_\pi = \alpha_\mu = 0$ and $\alpha_{\nu_\mu} = \alpha$), at some high energies $(m_\pi^2 - m_\mu^2)/\alpha < m_{\nu_\mu}$ pions cannot decay.

On the other hand, at some even higher energies, when $m_{\nu_\mu} + \alpha \vec{p}^{\,2}$,

ν_μ can decay $\nu_\mu \longrightarrow \pi + \mu$

These processes imply stringent constraints. But they are approximate and not correct. The decay constraint is obtained using energy-momentum conservation in the rest frame of pions, not in the laboratory frame. In VLI models they are not equivalent.

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Superluminal Neutrinos at OPERA Confront Pion Decay Kinematics

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Violation of Lorentz invariance (VLI) has been suggested as an explanation of the superluminal velocities of muon neutrinos reported by OPERA. In this Letter, we show that the amount of VLI required to explain this result poses severe difficulties with the kinematics of the pion decay, extending its lifetime and reducing the momentum carried away by the neutrinos. We show that the OPERA experiment limits $\alpha = (v_\nu - c)/c < 4 \times 10^{-6}$. We then take recourse to cosmic-ray data on the spectrum of muons and neutrinos generated in Earth's atmosphere to provide a stronger bound on VLI: $(v - c)/c < 10^{-12}$.

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Pion Decay Kinematics

Defining, in general (for massless particles and LIV), $\left\langle \frac{\partial E}{\partial p} \right\rangle = 1 + \alpha$

as the effective average from p_{min} up to the typical momenta of ~ 17 GeV of neutrinos, we write the energy-momentum relation

$$E_\nu = p_\nu (1 + \alpha)\,,$$

where α corresponds to VLI.

To avoid other constraints, assume all particles (except the neutrinos) have terminal velocity $c = 1$, and satisfy, $E_i = (p_i^2 + m_i^2)^{1/2}\,,$

The four vector of the decaying pion can then be written as $(E_\pi, p_\pi, 0, 0)$

and those of the final neutrino and muon can be given by

$$(E_\nu, p_{\nu\ell}, p_{\nu t}, 0) \text{ and } (E_\mu, p_{\mu\ell}, p_{\mu t}, 0)\,.$$

The longitudinal components of momenta are $p_{\nu\ell} = \eta p_\pi$ and $p_{\mu\ell} = (1-\eta) p_\pi$ and the transverse components are $p_{\nu t} = -p_{\mu t} = p_t$.

The energy conservation $E_\pi = E_\nu + E_\mu$, then gives (for large p_π and positive p_t^2:

$$\alpha\eta \leq \frac{1}{2p_\pi^2}\left[m_\pi^2 - \frac{m_\mu^2}{(1-\eta)}\right]$$

In OPERA average neutrino energy is ~ 17 GeV that arise from the decay of pions with a mean energy of ~ 60 GeV, so that the typical value of $\langle\eta\rangle \approx 0.3$.

We thus obtain a bound that rules out all models of VLI:

$$\alpha_{OPERA} \leq \frac{1}{0.6p_\pi^2}\left[m_\pi^2 - \frac{m_\mu^2}{0.7}\right] \sim 4 \times 10^{-6}\,.$$

Cosmic ray muon spectra at higher energies give stronger constraint on VLI

The observed differential energy spectrum is well represented by

$$\begin{aligned} f_\mu(E) \quad \cong \quad & \left[A_\pi\langle 1-\eta\rangle_\pi^{\beta-1}\left\{\frac{\langle 1-\eta\rangle_\pi\mathcal{E}_\pi}{E+\langle 1-\eta\rangle_\pi\mathcal{E}_\pi}\right\}\right. \\ & \left. A_K\langle 1-\eta\rangle_K^{\beta-1}\left\{\frac{\langle 1-\eta\rangle_K\mathcal{E}_K}{E+\langle 1-\eta\rangle_K\mathcal{E}_K}\right\}\right] E^{-\beta}\,, \end{aligned}$$

where $\beta =$ spectral index of the cosmic ray spectrum ~ 2.65; $\mathcal{E}_\pi = h_0(\theta) m_\pi / c\tau_\pi$; $\mathcal{E}_K = h_0(\theta) m_K / c$; τ_K; $A_{\pi/K} =$ Constants.
$h_0(\theta) = 7 \times 10^5 \sec\theta$ cm, the scale height of the Earth's atmosphere at a zenith angle θ $\tau_{\pi/K} =$ decay lifetimes of pions/kaons at rest
$\langle 1 - \eta \rangle_{\pi/K} =$ the fractional momenta carried away by the muons in pion/kaon decay averaged over the spectrum of cosmic rays, around the energy band of interest.

Considering the pion and kaon contributions and η distributions, we can arrive at the following bounds:

Muon spectra at Baksan fits very well with this theoretical estimate up to $\sim 4 \times 10^4$ GeV. Thus the muon data imply

$$\alpha < 10^{-11}\,.$$

Similarly the atmospheric neutrino spectrum up to ~ 400 TeV by the Ice-Cube Collaboration imply a constraint

$$\alpha < 10^{-13}\,.$$

To explain OPERA we need $\alpha \sim 10^{-5}$, which is not allowed by cosmic ray data.

Violation of Equivalence Principle

In weak field limit with Newtonian potential $\phi = GM/r \ll 1$ consider effective metric:

$$g_{44} = 1 - 2\alpha\phi \quad g_{ij} = -\delta_{ij}(1 + 2\gamma\phi) \, .$$ **In GTR, $\alpha = \gamma = 1$.**

Assuming $\gamma = 1$ and different α_i (VEP), the dispersion relation becomes:

$$E_0 = p + \frac{m^2}{2p} - \alpha\phi p \, ,$$

If two VEP states $|\nu_G\rangle = \begin{pmatrix} \alpha_1\phi p \\ \alpha_2\phi p \end{pmatrix}$ differ from the flavor eigenstates $|\nu_F\rangle = U(\theta_G)|\nu_G\rangle$, there can be neutrino oscillations.

In presence of both mass oscillation and VEP oscillation (with same mixing angles $\theta_M = \theta_G$), the oscillation length becomes

$$L = 2\pi \left[\Delta m^2/2p + p\phi\Delta\alpha\right]^{-1}$$

Cosmic rays data constraints VEP, because the dispersion relation is modified.

The Standard Model and the Higgs Scalar:

Strong Interaction: Force between the quarks – constituents of nucleons and mesons (hadrons)

Electromagnetic Interaction: Force between charged particles

Weak Interaction: Neutron decay $n \to p + e^- + \bar{\nu}$. Only left-handed particles take part in this interaction (charged current).

At energies above 250 GeV, they combine into Strong and Electroweak Interaction:

The Standard Model

Symmetry group $SU(3)_c \times SU(2)_L \times U(1)_Y$

breaks into $SU(3)_c \times U(1)_Q$

At higher energies before the symmetry breaking

$SU(3)_c$: 8 massless Gluons mediating strong interaction among quarks

$SU(2)_L$: 3 massless gauge bosons $W^{\pm,3}$, that interact with only the left-handed particles.

$U(1)_Y$: 1 massless gauge boson Y that couples to all charged fermions and the left-handed neutrinos

At lower temperature, after the symmetry breaking

$SU(3)_c$: 8 massless Gluons

$U(1)_Q$: massless photon

3 massive gauge bosons $W^{\pm}$ and Z.

When a left-handed particle ψ_L interacts with $W^{\pm,3}$, while a right-handed particle ψ_R does not, ψ_L and ψ_R remain massless and we have two particles ψ_L and ψ_R, both moving with a velocity c.

The gauge bosons $W^{\pm,3}, Y$ also move with a velocity c, two polarized states, no longitudinal modes.

We need a scalar particle (Spin-0): Higgs scalar

It's charged components $\phi^{\pm}$ become the longitudinal modes of $W^{\pm}$, making them massive;
one neutral component becomes longitudinal mode of Z;
which leaves only one physical Higgs particle.

As the left-handed fermions propagate, the interaction with Higgs scalars in the background mix them with right-handed fermions. So, they can become massive and move with velocity $v < c$.

Cosmological considerations

Matter and Energy in our Universe

Baryonic matter 5%

Dark Matter 25%

Dark Energy 70%

Challenges for Particle Physics

Matter dominance requires a small baryon asymmetry in the universe:

$$\frac{n_B}{s}=\frac{n_b-n_{\bar{b}}}{s}=(6.1^{+0.3}_{-0.2})\times 10^{-10}\,\frac{n_\gamma}{s}\Longrightarrow\frac{n_b-n_{\bar{b}}}{n_b}\approx 10^{-8}$$

How to generate such small B asymmetry?

Required B or L violation are not present in the SM

What are the candidates for Dark Matter?

SM does not have weakly interacting particles with required mass

What is the origin of DARK ENERGY?

Electroweak phase transition contributes 10^{56} times larger value

1) Why DE dominates now (in the past radiation and matter dominated)

2) Why DE is comparable to DM or ordinary matter

3) Is it DE or CC and what is its equation of state

Possible solutions

Lepton number violation associated with Neutrino masses can generate the required baryon asymmetry of the universe:

Leptogenesis

Generation of neutrino Majorana masses requires new Higgs scalars and right-handed neutrinos, which could be dark matter candidates

Condensates of light Majorana neutrinos could account for the dark energy

Summary

- We have not evidenced any violation of fundamental principles

- Severe constraints on violations of Lorentz invariance, equivalence principle, quantum mechanics, CPT, comes from precision tests of gravity, particle physics experiments, and also cosmic rays

- The Standard Model of particle physics has been extremely successful, although there are strong indications for new physics beyond the standard model

- Explanation of matter and energy densities in the universe also implies new physics

THANK YOU