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Photon-Neutrino Symmetry and the OPERA Anomaly

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Abstract

The OPERA collaboration has recently claimed discovery of superluminal propagation of neutrino beams. Excluding the possibility of unaccounted measurement errors, the most natural interpretation of OPERA anomaly is that, sufficiently far from the source, long-range neutrinos and photons may be regarded as components of the same field. In particular, we suggest that it is possible to construct a *neutrino-photon doublet* where the two components behave as dual entities. We examine conditions that enable the symmetry between neutrinos and photons to be unbroken. The benefit of this interpretation is that Lorentz invariance stays valid *regardless* of the relative velocity of neutrinos and their mean energy.

1.Introduction and motivation

The OPERA collaboration has recently claimed the discovery of superluminal propagation of neutrino beams [1]. OPERA has measured the velocity of neutrinos, as they travel from CERN to the Gran Sasso Laboratory (GSL) covering a distance of about 730 km. The CERN neutrino beam to GSL consists of ν_μ, with a small content of $\bar{\nu}_\mu$ (2.1%) and of ν_e or $\bar{\nu}_e$ (together less than 1%). Neutrinos travel through Earth structures with an average energy of E_{av} = 17.5GeV. Neutrino velocity is determined by taking the ratio between very accurate measurements of distance and time of flight. The distance is defined as the space separation between the emission point (where the proton beam extracted from the CERN site collides with a graphite target and creates secondary charged mesons that eventually decay into neutrinos) and the origin of the OPERA detector reference frame. High-accuracy GPS readings and optical triangulations led to a determination of the distance with an uncertainty of 20 cm (monitoring also Earth movements at the level of centimeters). An upgraded GPS-based timing system at CERN and GSL allows for time tagging with uncertainties at the level of less than 10 nanoseconds. The neutrino time of flight is then computed from a statistical comparison between the distribution of the neutrino interaction time and the proton probability density function matching the known time structure of the proton beam. The large data sample of neutrino events, recorded in a 3-year period, is claimed to have brought the statistical error in the analysis at the same level of the estimated systematic error.

Following this procedure, OPERA found the surprising result that neutrinos arrive 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 translates into a superluminal propagation velocity for neutrinos by a relative amount

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

where $\delta c_\nu \equiv {(\mathrm{v}_\nu - c)}/{c}$. The same measurement was previously performed by MINOS (which has a 735 km baseline and a broad neutrino energy spectrum peaked around 3 GeV). Although not statistically significant, the MINOS result has a central value in the same ballpark of the recent OPERA determination [2]

$$\delta c_\nu = (5.1 \pm 2.9) \times 10^{-5} \quad \text{(MINOS)}$$

Earlier short-baseline experiments have set upper limits on $|\delta c_\nu|$ at the level of about 4 x 10^{-5} in an energy range between 30 and 200 GeV [3]. However, observations of $E_{av} \cong 10$ MeV neutrinos from supernova SN1987a provide a constraint of [3]

$$\delta c_\nu < 4 \times 10^{-9} \quad \text{(SN1987a)}$$

We develop here a field-theoretical solution to the OPERA anomaly that

1) is fully compliant with Lorentz invariance, regardless of neutrino mean energy E_{av} and relative velocity δc_{ν} ,

2) does not invoke the contribution of second-order effects on neutrino emission, propagation and detection.

Our premise is that the only way to reconcile OPERA results with Special Relativity is to accept that, under certain circumstances, an inherent symmetry exist between *long-range neutrinos* and *light signals in vacuum*. Inspired by the philosophy of supersymmetry program, we seek to construct the analog of a gauge doublet that combines Maxwell fields (A_{μ}) with Weyl fermions describing single-flavor neutrinos (ν).

This brief report is organized as follows: next section briefly surveys the constraints related to unbroken supersymmetry. Conditions leading to suppression of neutrino oscillations in matter are touched upon in section 3. Formulation of photon-neutrino symmetry is developed in sections 4 and 5. Concluding remarks are presented in the last section.

2. Supersymmetry: a summary description

Supersymmetry postulates that *bosons* (particles of zero or integral spin) and *fermions* (particles of half-integer spin) can be grouped in the same doublet and that there is a *supercharge operator* Q that turns fermions into bosons and viceversa [4]. Let $|f\rangle$ and $|b\rangle$ denote fermionic and bosonic fields. The action of supercharge operator is as follows:

$$Q|f\rangle = |b\rangle$$

$$Q|b\rangle = |f\rangle$$

The operators Q and Q^+ are *spinors*, that is, they behave as spin-½ operators under Lorentz transformations. If P^μ denotes the conserved four-momentum, Q and Q^+ satisfy the algebra

$$[Q,Q^+]=P^\mu$$

$$[Q,Q]=[Q^+,Q^+]=0$$

$$[Q,P^\mu]=[P^\mu,Q]=0$$

To represent an unbroken symmetry, bosons and fermions transforming under the supercharge operator must satisfy three constraints. They must have:

- Equal rest-frame mass ($m_b = m_f$),
- Same number of components (degrees of freedom),
- Same quantum charges (such as electrical and weak isospin charges).

We shall use these properties in the remainder of the paper.

3. Neutrino oscillations in matter

Experiments with solar, atmospheric, reactor and accelerator neutrinos have provided compelling evidence for oscillations caused by nonzero neutrino masses and mixing [5]. These oscillations represent transitions in flight between the three flavor neutrinos ν_e,ν_μ,ν_τ (and their respective antiparticles). The existence of flavor neutrino oscillations implies that, if a neutrino of a given flavor, say ν_μ, with energy E is produced in some weak interaction process, at a sufficiently large distance L from the ν_μ source, the probability to find a neutrino of a different flavor, say ν_τ, $P(\nu_\mu \to \nu_\tau; E,L)$ is different from zero. It follows that the probability that ν_μ stays unchanged and does not turn into a different flavor (the "survival" probability) $P(\nu_\mu \to \nu_\mu; E, L)$ is smaller than one. In the formalism of local quantum field theory, neutrino oscillations are a consequence of neutrino mixing and are given by

$$\nu_{\alpha L}(x) = \sum_j U_{\alpha j} \nu_{jL}(x) \qquad (\alpha = e, \mu, \tau)$$

Here, $\nu_{\alpha L}(x)$ are the left-handed flavor neutrino fields, $\nu_{jL}(x)$ are the left-handed massive neutrino fields having masses $m_j \neq 0$ and U is the unitary mixing matrix. It can be shown that, in the case of 3-neutrino mixing, transition and survival probabilities depend on mass squared differences $\Delta m_{kj}^2 \equiv m_k^2 - m_j^2$ with [5]

$$\left|\Delta m_{21}^2\right| \cong 7.6 \times 10^{-5} eV^2$$

$$\left|\Delta m_{31}^2\right| \cong 2.4 \times 10^{-3} eV^2$$

In case of 3-neutrino mixing in Earth matter and for neutrinos energies $E_{av} > 2$ GeV, effects due to Δm_{21}^2 in oscillation probabilities can be neglected up to leading order [5]. This is because the mean electron densities in the Earth matter are such that oscillations due to Δm_{21}^2 are suppressed. Under the additional constraint $\Delta m_{31}^2 < 0$, it can also be shown that both $\nu_{e(\mu)} \to \nu_{\mu(e)}$ and $\nu_e \to \nu_\tau$ oscillations are further suppressed. The absence of neutrino oscillations motivates the hypothesis that neutrinos have vanishingly small masses, in order to comply with Lorentz invariance [6]. In different words,

$$\Delta m_{31}^2 < 0 \Rightarrow P(\nu_\alpha \to \nu_{\alpha'}; E, L) << 1 \Rightarrow m_\nu << 1\ eV$$

This is the case we are considering below.

4. Assumptions

4.1) It is well established that neutrinos and antineutrinos participate in either charged current (CC) and neutral current (NC) electroweak interactions, where CC are carried by the weak $W^{\pm}$ bosons and NC by the Z^0 boson. The energy range of electroweak interactions is on the order of $\mu_{EW} = O(G_F^{-1/2}) \approx 300\,\text{GeV}$ where G_F represents the Fermi constant. We assume that, for propagation distances well above μ_{EW}^{-1}, neutrinos loose memory of electroweak interaction. As a result, their weak isospin charge goes to zero ($T_3 = 0$).

4.2) If the distance range covered by neutrino flight (x) falls within μ_{EW}^{-1} and the neutrino oscillation length in Earth matter L_m, that is if $\mu_{EW}^{-1} << x < L_m$ and if neutrino oscillations are suppressed by the condition $\Delta m_{21}^2 << 1\ \text{eV}^2$ and $\Delta m_{31}^2 < 0$, then photon-neutrino symmetry is nearly unbroken and neutrinos have rest-frame masses consistent with zero ($m_\nu << 1$ eV).

5. Photon-neutrino symmetry

Propagating degrees of freedom in a photon-neutrino doublet are Maxwell field A_μ and a two-component Weyl neutrino ν. The Lagrangian density for the doublet is given by [4]

$$L_{PN} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\nu^{+} \bar{\sigma}^{\mu} \partial_\mu \nu + \frac{1}{2} D^2$$

Here, the barred Pauli matrices are, respectively,

$$\bar{\sigma}^0 = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix},\ \bar{\sigma}^1 = \begin{pmatrix} 0 & -1 \\ -1 & 0 \end{pmatrix},\ \bar{\sigma}^2 = \begin{pmatrix} 0 & i \\ -i & 0 \end{pmatrix},\ \bar{\sigma}^3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

The on-shell degrees of freedom for A_μ and ν are represented by 2 bosonic and 2 fermionic helicity states. However, off-shell ν consist of 2 complex (or 4 real) fermionic degrees of freedom, whereas A_μ has three degrees of freedom with one degree being removed through a gauge transformation. To maintain consistency off-shell, it is customary to include in the Lagrangian one real bosonic auxiliary field, traditionally called D that satisfies $D = D^*$ and has dimensions of [mass]^2. Since it has no kinetic term in the Lagrangian, D can be eliminated on-shell. The action built from this Lagrangian stays invariant to the following transformations of fields

$$\delta A_\mu = -\frac{1}{\sqrt{2}}(\varepsilon^+ \overline{\sigma}_\mu \nu + \nu^+ \overline{\sigma}_\mu \varepsilon)$$

$$\delta \nu = \frac{i}{2\sqrt{2}}(\sigma^\mu \overline{\sigma}^\nu \varepsilon) F_{\mu\nu} + \frac{1}{\sqrt{2}} \varepsilon D$$

$$\delta D = \frac{i}{\sqrt{2}}(-\varepsilon^+ \overline{\sigma}^\mu \partial_\mu \nu + \partial_\mu \nu^+ \overline{\sigma}^\mu \varepsilon)$$

in which parameter ε represents an anti-commuting spinor [4].

6. Conclusions

Neutrinos are matter particles distinguished from photons by their spin, rest-frame mass and weak isospin charge. However, since *far enough* from their source, long-range neutrinos no longer participate in weak interactions, their weak isospin charge becomes irrelevant ($T_3 = 0$). Thus, under conditions that enable suppression of flavor oscillation in Earth matter, neutrinos and photons may be considered as partners of the same gauge doublet. The underlying symmetry is nearly unbroken because the two partners are close to being on-shell, share the same rest-frame mass ($m_\gamma = 0,\ m_\nu \approx 0$), same number of degrees of freedom (2 helicity states for both neutrinos and photons) and the same set of quantum numbers ($q = T_3 = 0$). This interpretation of OPERA anomaly preserves Lorentz invariance *regardless* of the mean energy carried by the neutrino beam (E_{av}) and its velocity relative to the luminal velocity in vacuum (δc_ν). Our conclusions are reported below.

$x = O(\mu_{EW}^{-1})$	Spin	Rest-frame mass (m)	Electric charge (q)	Weak Isospin (T_3)
Photon (γ)	1	0	0	0
Neutrino (ν)	1/2	> 0	0	1/3

Tab.1: Photon and neutrino properties for $x = O(\mu_{EW}^{-1})$

$\mu_{EW}^{-1} << x < L_m$	Spin	Rest-frame mass (m)	Electric charge (q)	Weak Isospin (T_3)
Photon (γ)	1	0	0	0
Neutrino (ν)	1/2	≈ 0	0	0

Tab. 2: Photon and neutrino properties for $\Delta m_{21}^2 << 1\ \text{eV}^2, \Delta m_{31}^2 < 0$ and $\mu_{EW}^{-1} << x < L_m$

On-line References

[1] http://arxiv.org/abs/1109.4897

[2] http://prd.aps.org/abstract/PRD/v76/i7/e072005 and http://arxiv.org/abs/0706.0437

[3] http://arxiv.org/abs/1109.5682

[4] http://arxiv.org/abs/hep-ph/9709356

[5] http://pdg.lbl.gov/2011/reviews/rpp2011-rev-neutrino-mixing.pdf

[6] http://en.wikipedia.org/wiki/Lorentz-violating_neutrino_oscillations