Apparent Lorentz violation with superluminal Majorana-tachyonic neutrinos at OPERA?

F Tamburini\(^1,2\) and M Laveder\(^3,4\)

\(^1\) Department of Physics and Astronomy, University of Padova, vicolo dell’osservatorio 3, Padova, Italy
\(^2\) CIVEN, Torre Hammon, Marghera, Venezia
\(^3\) Department of Physics and Astronomy, University of Padova, via Marzolo 8, Padova, Italy
\(^4\) INFN, Sezione di Padova, Padova, Italy

E-mail: fabrizio.tamburini@unipd.it and marco.laveder@unipd.it

Received 8 January 2012
Accepted for publication 30 January 2012
Published 27 February 2012
Online at stacks.iop.org/PhysScr/85/035101

Abstract

From the controversial data release of the OPERA–CNGS experiment (The OPERA collaboration 2011 arXiv:1109.4897), publicly announced on 23 September 2011 where muonic neutrinos seem to propagate at a speed faster than light, we cast a phenomenological model describing the behaviour of such a tachyonic neutrino, carrying an imaginary mass based on the Majorana tower of particles described in 1932. If the interpretation of OPERA data is correct and considering the strong constraints from the observations of the supernova SN1987a, we show that the tachyonic behaviour of the neutrino can occur only when it is propagating inside matter. Following this idea, within the experimental errors, we fit the data released by OPERA with those of MINOS and by assuming a superluminal propagation inside the matter of SN1987a, we confirm our ansatz with stellar structure models of the supernova precursor. Monte Carlo simulations based on this fit agree well with the new OPERA data. Possible violations of Lorentz invariance due to quantum gravity effects have been considered.

PACS numbers: 14.60.Lm, 13.20.Cz, 14.60.St

(Some figures may appear in colour only in the online journal)

1. Introduction

The data released by OPERA on 23 September 2011 indicate that an anomalous propagation of muon neutrinos (ν\(_\mu\)) mainly produced in the decay, \(\pi^+ \rightarrow \mu^+ + \nu_\mu (\bar{\nu}_\mu)\), occurred when they traversed in 2.45 × 10\(^{-3}\) s the distance of 731.3 km inside the Earth’s crust, separating Geneva and Gran Sasso Laboratories. The data released by CERN and Gran Sasso comprise 16 111 events detected and correspond to about 10\(^{20}\) protons on the target collected during the 2009, 2010 and 2011 CNGS runs. If this result is free from systematic errors and with a correct interpretation, it would indicate that ν\(_\mu\)s could actually propagate with a superluminal speed, namely \((v - c)/c = (2.48 \pm 0.28 \text{ (stat)} \pm 0.30 \text{ (sys)}) \times 10^{-5}\). The effective resulting distance measured with GPS was 731 278.0 ± 0.2 m. The peak of neutrino detection occurs ~6 × 10\(^{-8}\) s earlier than expected, with a precision of 6.9 (stat)–7.4 (sys) ns, which, with 6σ accuracy, means 2.48 × 10\(^{-5}\) times smaller than the light propagation time. The overall systematic uncertainty is obtained by assuming independent error sources. This anomaly was confirmed, with 6.2σ confidence level, by the new results released on 18 November 2011, with \((v - c)/c = (2.37 \pm 0.32 \text{ (stat)}^{+0.34}_{-0.24} \text{ (sys)}) \times 10^{-5}\). The anticipation with respect to the light time of flight is 62.1 ± 3.7 ns, in agreement with the 57.8 ± 7.8 (stat)\(^{+8.3}_{-5.0}\) (sys) ns obtained with the main new analysis as reported in versions v1 and v2 of [1].

If the OPERA results are correct, neutrinos should behave either as if they had a pseudo-tachyonic behaviour, such as photons propagating in metamaterials or, more simply, as tachyons. In the first case, neutrinos have an apparent superluminal behaviour similar to that of photons in a metamaterial without violating causality [2–4]. This effect seems to be forbidden according to the recent claim by Cohen
and Glashow (hereafter CG) [5]; no pseudo-superluminal motion in OPERA could have occurred with standard model muonic neutrinos because of the disruption of the beam shape expected from the effects induced by weak-current phenomena. Such a neutrino should produce electron/positron pairs, radiating away its energy. This effect has not been observed either through a deformation of the energy spectrum of the OPERA neutrino beam or through the detection of Cherenkov radiation from ICARUS [6] or from the detection of radio signals from the Moon in other experiments [7].

Superluminal propagation is usually associated with quantum gravity (QG) phenomena and/or with the violation of the Lorentz invariance (LI). For this reason, energetic neutrinos are expected to propagate faster than the speed of light $c$ [8, 9], representing one of the best candidates to reveal QG phenomena [10]. Recent analyses of the light from the farthest quasars observed with the Hubble Space Telescope [11] and from the propagation of gamma rays from INTEGRAL/IBIS observations of GRB041219A [12] demonstrate, instead, that the scales at which QG fluctuations are expected to occur and violate LI are much closer to the fundamental Planck scale than that invoked in the literature to explain neutrino superluminality. If these QG limits apply to neutrinos, the muonic neutrinos produced by OPERA would be free of these effects. A stringent limit on superluminal propagation inside matter are compatible with those provided by stellar structure models.

2. Tachyonic neutrino model?

To model a tachyonic neutrino behaviour based on the OPERA anomaly, we adopt a particular solution of the Majorana infinite-spin component equation [18, 19], also known as Majorana tower [20], and build a phenomenological model of a spin $s = 1/2$ particle carrying imaginary mass. The generality of this type of solution permits us to sketch the main characteristics expected from such a tachyonic neutrino, independently of the physical causes leading to a possible actual superluminal behaviour. The properties of this hypothetical particle with imaginary mass are given by a fit of the experimental results available in the literature.

In his original work, Ettore Majorana formulated a particular solution of the Dirac equation with positive-definite mass solution,

$$\frac{W}{c} + \alpha \cdot p - \beta mc = 0, \quad (1)$$

where $\Psi$ is the wavefunction, $\alpha$ and $\beta$ are the Dirac matrices, $m$ is the mass of the particle, $p$ the momentum and $W$ the energy [21, 22]. From the relativistic formulation of the mass and energy, the energy of the particle is $W = \pm \sqrt{c^2 p^2 + m^2 c^4}$. The indetermination in the sign, interpreted by Dirac in terms of particle and antiparticle states, can be overcome by finding an infinite spectrum of positive definite rest mass solutions to the Dirac equation, for any spin value. The solutions to equation (1), expressed in terms of plane-wave solutions with positive-definite mass, are obtained through a relativistic transformation of null-spin angular momentum waves. The energy states for any spin value are given by

$$W_0 = m^* c^2 \frac{s}{s + 1/2}, \quad (2)$$

the parameter $m^*$, also known as the Majorana mass term, is half the rest mass of the null-spin particle state, and the intrinsic angular momentum parameter, $s$, is the corresponding spin solution that can be of scalar, bosonic or fermionic type.

Equation (2) implies that particles with different intrinsic angular momenta and with the same Majorana mass, $m^*$, have different rest mass values. The relationship linking spin and mass is valid for bosonic ($s = 1, 2, 3, \ldots$), fermionic ($s = 1/2, 3/2, 5/2, \ldots$) and scalar particles, $s = 0$,

$$M = m^* \frac{s}{s + 1/2}. \quad (3)$$

Equation (3) describes an infinite spectrum of particles with positive-definite mass values that decrease with the spin angular momentum of the particle. Photons in vacuum represent a particular solution of the bosonic case with zero rest mass. In addition to states with positive-definite mass
values, there are other solutions found and discussed by Majorana himself, for which energy is related to momentum through $W = \pm \sqrt{c^2 p^2 - k^2 c^2}$ and they exist for all the positive values of $k$ for which $p \geq kc$ holds. This model is based on the group of infinitesimal Lorentz transformations, and for a single detection event LI is thought to be not violated [23], even if the problem of tachyons and causality has not been completely understood [24, 25]. Those states can be considered as belonging to the class of solution with imaginary mass term $M = ik$ [18]. In this case, the Majorana mass–spin relationship then becomes $m^2 = M^2 \left( s + \frac{1}{2} \right)^2 = -k^2$.

When interacting with structured matter, neutrinos are expected also to acquire orbital angular momentum (OAM) and behave like a Majorana particle [20, 26, 27] obeying a more general mass/angular momentum relationship

$$M = \frac{m^*}{\Sigma(\ell, q) + 1/2},$$

where $\Sigma(\ell, q)$ is a general function of the spin $s = 1/2$ and OAM $\ell$ of the photon and of the characteristic spatial scale of the perturbation $q$; the Majorana mass term coincides with that acquired by the neutrino in the unperturbed medium. A similar effect is expected also when a beam of neutrinos crosses a Petrov-type D gravitational fields like that of a rotating black hole [28]. Thus, differently from the space–time manifold structure of the Lorentz group, in which space is homogeneous and isotropic and time homogeneous, a medium can exhibit peculiar spatial structures that break the space–time symmetry. In this case, for the peculiar solution with imaginary mass state, the mass–spin angular momentum relationship is replaced by a mass–total angular momentum relationship, $m^2 = -k^2 \left( \Sigma(\ell, q) + \frac{1}{2} \right)^2$. This additional effect could give an additional hint to model the pulse and thus the time of arrival of neutrinos, because the OAM-induced mass would act as a negative mass term induced by inhomogeneities of the medium. Another behaviour related to the presence of structured matter is the onset of parametric resonances on neutrino states [29].

### 2.1. Tachyonic neutrino effects in dense media?

By assuming that the OPERA results have a real physical cause, one must then take into account the stringent limits of superluminal propagation based on the results of the $\overrightarrow{\nu}_e$s detected from SN1987a. In fact, the anticipation of $\sim 60$ ns, applied to the SN neutrinos, would have implied the detection of a neutrino peak years before the optical detection of the SN event, and this was not the case.

The remaining hypothesis that could fit the OPERA anomaly, the still unclear results from MINOS relative to the neutrino propagation timing [30] and those of SN1987a, is to assume that these tachyonic properties of neutrinos cannot occur in vacuum or because of QG effects but only when propagating either inside matter or in a gravitational field. This ansatz implies that also the $\overrightarrow{\nu}_e$s from SN1987a propagating inside matter of the SN precursor should distribute according to a linear relationship involving the tachyonic imaginary mass and energy together with the results of MINOS and OPERA, as expected from a superluminal particle, and the additional contribution of the interstellar medium during the travel of the neutrino beam can be neglected.

If the neutrino tachyonic behaviour is expected only during the propagation inside a medium, an energy loss of the neutrino beam via the Cherenkov effect has to be taken into account [5]. The CG effect states that no superluminal motion of standard-model neutrinos can explain the OPERA anomaly without dramatically modifying the energy spectrum of the initial neutrino beam mainly because of the effects induced by weak-current phenomena. An energetic standard-model neutrino, travelling faster than light in that medium, is expected to produce electron/anti-electron pairs that radiate away the neutrino energy. This radiation has not been observed either with OPERA [1], ICARUS [6], or from other experiments searching for radio signal emissions from the Moon generated by the Cherenkov radiation mechanism [7]. Thus, we agree with CG conclusions that standard model tachyonic neutrinos cannot be reconciled with the OPERA results.

The initial hypothesis of tachyonic propagation inside the Earth’s crust must be restricted to beyond-standard model neutrinos carrying an imaginary mass $ik$ obeying $p \geq kc$. In fact, in the case of a tachyonic behaviour and standard dispersion relation, the pair production would require that $E_i^2 - p_i^2 > (2m_e)^2$, not satisfied by an imaginary mass value. To be valid, we must consider a modified energy dispersion relationship of the form $E^2 = p^2 + M^2 + F$, where $F$ is an arbitrary function. Here, $p$ should be considered as the conjugate momentum, so that, in principle, $p$ and $F$ should depend on space–time coordinates as discussed, e.g., in the LI violation hypothesis or from a dependence on the temperature [31]. However, the latter hypothesis must be better refined to fully reconcile with the SN parameters. It is clear that, depending on the characteristics of $p$ and $F$, these neutrinos can forbid the CG pair production. The imaginary mass, in this case, is $\sqrt{M^2 + F}$ with $F$ negative.

### 2.2. Fit of MINOS, OPERA and SN1987a data

We now test our conjecture by comparing the results of OPERA, MINOS and those obtained from the propagation of the electronic anti-neutrinos only inside the matter of SN1987a. If these neutrinos obey the Majorana tachyonic condition, $p \geq kc$, independently of their flavour and follow the same distribution as for OPERA and MINOS, then the tachyonic behaviour should have occurred only because of the interaction inside the SN matter and, in vacuum, neutrinos would propagate at a speed less than or equal to that of light. In table 1, we report the averaged neutrino energies for OPERA (1–2–3) and MINOS and those calculated for SN1987a, the absolute value of the relative time anticipation $\Delta T/T_0$, and the imaginary mass terms with the associated errors. The mass–energy relationship is obtained from the relationship $M^2 = 2E^2\Delta T/T_0$ discussed in [32, 33].

To calculate the neutrino mass during propagation in the SN medium, we proceed with two independent approaches. In the first one, we calculated the neutrino propagation as it had a path length $l_{SN}$ inside a shell of matter with averaged density equivalent to that of the Earth’s crust. The parameters of the SN considered here were taken from those of its precursor,
Imaginary Majorana mass (GeV)

Figure 1. Neutrino imaginary mass versus energy. The neutrinos propagating inside SN1987a and those from MINOS and OPERA data are distributed along a single line, indicating the presence of a variable tachyonic imaginary mass satisfying the tachyonic condition $p \geq kc$. Inset: zoom of the SN-3 dataset.

Sanduleak $–69^\circ$ 202a, just before the SN explosion, a blue supergiant with radius $(1.8–4) \times 10^{12}$ cm and a mass of $3.96 \times 10^{10}$ g; more details can be found in [34]. Assuming that there are no tachyonic effects in vacuum, then the time anticipation calculated considering the propagation $l_g$ in free space is

$$\frac{\Delta T}{T_0} = \frac{\langle \rho \rangle_{\text{SN}}}{\langle \rho \rangle_{\odot}} \frac{l_g}{l_{\text{SN}}} \left[ \frac{|v-c|}{c} \right],$$

where $T_0$ is the photon flight time needed to cross the SN distance, $\langle \rho \rangle_{\text{SN}} \sim (1.6 – 9.1) \times 10^{-2}$ g cm$^{-3}$, the averaged densities of the SN, obtained by assuming a $10^{12}$ cm and a $1.8 \times 10^{12}$ cm radius, respectively, a different value from the $4 \times 10^{11}$ cm as suggested by stellar structure studies. The values of energy and mass so derived are reported in table 1 as SN-1 and SN-2. The second approach is based on the idea that the neutrino burst detected by Hirata $et$ al [13] at 20 MeV, indicating the formation of a neutron star, was actually affected by this pseudo-tachyonic behaviour (SN-3) and, interestingly, coincides with the result of SN-2. In the inset of figure 1 we also see that there are three values with a slightly different distribution that do not fit the interpolation obtained by combining the OPERA and MINOS data, a double linear distribution already discussed by Huzita in 1987 [32].

Table 1. Columns 1 and 2 show datasets and corresponding averaged neutrino energies for OPERA, MINOS and those calculated for the supernova SN1987a. The third column gives the absolute value of the relative time anticipation $\Delta T/T_0$. Columns 4 and 5 give the imaginary neutrino mass terms and their associated errors.

| Dataset | $E$ (GeV) | $\Delta T/T_0$ | $k$ (GeV) | $\Delta k$ |
|---------|-----------|----------------|-----------|------------|
| OPERA 1 | 42.9      | $2.76 \times 10^{-5}$ | 0.317 | 0.093 |
| OPERA 2 | 17        | $2.48 \times 10^{-5}$ | 0.119 | 0.028 |
| OPERA 3 | 13.9      | $2.18 \times 10^{-5}$ | 0.092 | 0.035 |
| MINOS   | 3         | $5.10 \times 10^{-5}$ | 0.030 | 0.017 |
| SN-1    | $2 \times 10^{-2}$ | $1.17 \times 10^{-1}$ | 0.009 | 0.006 |
| SN-2    | $2 \times 10^{-2}$ | $2.00 \times 10^{-2}$ | 0.004 | 0.001 |
| SN-3    | $2 \times 10^{-2}$ | $2.00 \times 10^{-2}$ | 0.004 | 0.001 |

Figure 2. Histogram of the absolute values of the time anticipation $\Delta T$ of neutrinos with respect to light of the Majorana tachyonic model. In the inset are reported the new data released by OPERA. The phenomenological model of the tachyonic Majorana neutrino gives an averaged value $\Delta T = 61.95 \pm 0.37$ ns with rms = 11.73 ns that fits well with the value $62.1 \pm 3.7$ ns and rms = 16.4 reported in the OPERA data.

Our phenomenological model shows good agreement also with the new OPERA results. The energy and momentum values follow a linear distribution, $k = p_1 E + p_2$, with 95% confidence bounds. The fitting parameters and their intervals are $p_1 = 0.006727 (0.005509, 0.007945)$ GeV, std. dev. = 0.000609 and $p_2 = 0.006884 (0.005824, 0.007945)$ GeV, std. dev. = 0.000530 GeV, which is the tachyonic mass term of the neutrino in the limit $p = kc$. The sum of squares due to error SSE = 0.6483 and the root mean square error RMSE = 0.4026 indicate that the properties of $\tilde{\nu}$s inside the SN are in good agreement, with minor deviations, from the OPERA and MINOS results. All apparently obey the tachyonic relationship $p \geq kc$ and the linear relationship between mass and energy. We generate with a Monte Carlo simulation a string of 1000 neutrino events and compare the time anticipation values $\Delta T$, by using the relationships $\Delta T = 1/2 T_0 M^2/E^2$, $M = i k$ and the linear interpolation $k = p_1 E + p_2$, with the new OPERA dataset. The values of the parameters $p_1$ and $p_2$ were generated according to a normal distribution and the energy values were generated according to the muon neutrino fluxes at Gran Sasso$^5$ and weighted for the neutrino cross section. We do not find clear evidence of energy dependence with time anticipation $\Delta T$ in the OPERA energy domain if we follow the most conservative approach adopted by the OPERA team. The averaged values of the time anticipations as a function of energy at the two values 13.9 and 40.7 GeV are $\Delta T = (54.7 \pm 18.4 \text{ (stat)} \pm 7.3 \text{ (sys)})$ ns and $\Delta T = (68.1 \pm 19.1 \text{ (stat)} \pm 6.9 \text{ (sys)})$ ns. The simulations show excellent agreement with the new OPERA data as shown in figure 2.

3. Conclusions

The OPERA anomaly is still a controversial issue. Until now, no clear explanation of this hypothetical superluminal

http://www.mi.infn.it/psala/icarus/nugsweb2005/nugs2005numu.flu
propagation of muonic neutrinos has been found that is able either to disprove or to validate this experimental result. We propose a phenomenological description, without invoking QG effects, based on the tachyonic solution of the infinite-spin component equation by Majorana to see whether this anomaly can be due to new physics or simply leads to some logical contradictions. To this end, we fitted the energy and mass values of the neutrino events measured in OPERA and MINOS experiments including those of the supernova SN1987a, imposing the additional condition that the superluminal behaviour must have occurred only inside the shell of matter of the SN progenitor [35]. In vacuum, however, neutrinos are expected to propagate at a speed less than or equal to that of light; otherwise the anticipation observed in the SN1987a would have been of years duration. Following these assumptions, we find that the mass and energy values are distributed according to a linear relationship, as expected from a tachyonic behaviour and Monte Carlo simulations of this model fit with excellent agreement with the new OPERA data. The only thing we can conclude is that either this distribution is due to a real physical cause or it can be due to the uncertainties present in the measurements from MINOS and SN1987a. Only future MINOS results will be able to settle this issue.

Moreover, the lack of detection and energy loss from the Cohen and Glashow radiation mechanism from ICARUS and the invariance of the energy spectrum of the neutrinos detected at Gran Sasso invalidates any apparent or real tachyonic behaviour with standard model neutrinos. These superluminal neutrinos do not satisfy the requirements of the classical theory related to the modelling of the neutrino production from pion decay and with neutrino oscillations [33]. All this seems to disfavour the OPERA results, unless one assumes that for the muonic neutrinos produced in this experiment, when crossing the material inside the Earth’s crust, the stellar structure of the SN1987a progenitor must have the properties of a beyond-standard model neutrino with tachyonic properties only when propagating inside matter. A possible explanation for this behaviour might be sterile neutrino mixing, confined inside a region where a gravitational field is present, or that the presence of matter/gravitational field introduces a preferred reference frame, violating the LI and/or CPT symmetry, or an environmental temperature effect.

If these neutrino properties are confirmed, they will not only give crucial information on the astrophysics of SN explosions, compact objects, stellar interiors and cosmology [36], but will also revolutionize the standard model of particles [37] and its extension to Lorentz-violating phenomenologies [38]. If confirmed in a more general scenario, the Majorana theory can also predict the neutral Higgs boson mass: from equation (3), the mass of the spin 0 particle is three times that of $Z^0$, i.e. $m = (273.56 \pm 0.01) \text{ GeV}$. Only future experiments will contribute to solving the puzzling problem of neutrino propagation in matter.

Acknowledgments

The authors thank Carlo Giunti, Antonio Masiero, Marco Matone, Massimo Della Valle and Cesare Chiosi for helpful discussions.

References

[1] The OPERA Collaboration 2011 arXiv:1109.4897
[2] Pendry J, Schurig D and Smith D 2006 Science 312 1780
[3] Ziolkowski R 2001 Phys. Rev. E 63 046604
[4] Smolyaninov I 2011 J. Opt. 13 024004
[5] Cohen A G and Glashow S L 2011 arXiv:1109.6562v1
[6] The ICARUS Collaboration 2011 arXiv:1110.3763
[7] Stål O et al 2007 Phys. Rev. Lett. 98 071103
[8] Ellis J et al 2008 Phys. Rev. D 78 033013
[9] Sakharov A et al 2009 J. Phys.: Conf. Ser. 171 012039
[10] Movromatos N E et al 2008 Phys. Rev. D 77 053014
[11] Tamburini F, Cufano C, Della Valle M and Gilmozzi R 2011 Astron. Astrophys. 533 A71
[12] Laurent P et al 2011 Phys. Rev. D 83 121301
[13] Hirata P et al 1987 Phys. Rev. Lett. 58 1490
[14] Cullen S and Perelstein M 1999 Phys. Rev. Lett. 83 268
[15] Arnet W, Bahcall J, Kirshner R and Woosley S 1989 Annu. Rev. Astron. Astrophys. 27 629
[16] Wolfenstein L 1978 Phys. Rev. D 17 2369
[17] Mikheev S P and Smirnov A Y 1985 Sov. J. Nucl. Phys. 42 913
[18] Mikheev S P and Smirnov A Y 1985 Yad. Fiz. 42 1441
[19] Majorana E 1932 Nuovo Cimento 9 335
[20] Majorana E 1937 Nuovo Cimento 14 171
[21] Tamburini F and Thidé B 2011 Europhys. Lett. 96 64005
[22] Dirac P A M 1928 Proc. R. Soc. Lond. A 117 610
[23] Thaller B 1992 The Dirac Equation (Berlin: Springer)
[24] Feinberg G 1967 Phys. Rev. 159 1089
[25] Girard R and Marchildon L 1984 Found. Phys. 14 535
[26] Nikolici H 2006 Found. Phys. Lett. 19 259
[27] Mendonça J and Thidé B 2008 Europhys. Lett. 84 41001
[28] Tamburini F, Sponselli A, Thidé A and Mendonça A 2010 Europhys. Lett. 90 45001
[29] Tamburini F, Thidé B, Molina-Terriza G and Anzolin G 2011 Nature Phys. 7 195
[30] Akhmedov E 2000 Pramana 54 47
[31] Akhmedov E 2001 Phys. At. Nucl. 64 787
[32] Adamson P et al 2007 Phys. Rev. D 76 072005
[33] Matone M 2011 arXiv:1109.6631
[34] Huzita H 1987 Mod. Phys. Lett. A 2 905
[35] Drago A, Masina I, Pagliara G and Tripiccione R 2011 arXiv:1109.5917
[36] Petschek A (ed) 1990 Supernovae (New York: Springer)
[37] Woosley S and Weaver T 1986 Annu. Rev. Astron. Astrophys. 24 205
[38] Itoh N, Hayashi H, Nishikawa A and Kohyama Y 1996 Astrophys. J. Suppl. 102 411
[39] Yao W et al 2006 J. Phys. G: Nucl. Part. Phys. 33 1
[40] Colladay D and Kostelecký V 1998 Phys. Rev. D 58 116002

