The hypothesis of superluminal neutrinos: Comparing OPERA with other data

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Abstract – The OPERA Collaboration reported evidence for muonic neutrinos traveling slightly faster than light in vacuum. While waiting further checks from the experimental community, here we aim at exploring some theoretical consequences of the hypothesis that muonic neutrinos are superluminal, considering in particular the tachyonic and the Coleman-Glashow cases. We show that a tachyonic interpretation is not only hardly reconciled with OPERA data on energy dependence, but that it clashes with neutrino production from pion and with neutrino oscillations. A Coleman-Glashow superluminal neutrino beam would also have problems with pion decay kinematics for the OPERA setup; it could be easily reconciled with SN1987a data, but then it would be very problematic to account for neutrino oscillations.

Introduction. – Recently the OPERA Collaboration [1] reported an early arrival time for CNGS muon neutrinos with respect to the one expected assuming neutrinos to travel at the speed of light in vacuum c. The relative difference of the velocity of the muon neutrinos ν with respect to light quoted by OPERA is

\[ \frac{v - c}{c} = (2.48 \pm 0.28 \text{(stat)} \pm 0.30 \text{(sys)}) \times 10^{-5}, \] (1)

for a mean energy of the neutrino beam of 17 GeV.

Similar hints, but with much less significance, were also reported for muon neutrino beams produced at Fermilab. Dealing with energies peaked at 3 GeV, the MINOS Collaboration [2] found in 2007 that \( (v - c)/c = (5.1 \pm 3.9) \times 10^{-5} \). In 1979, a bound on the relative velocity of the muon with respect to muon neutrinos (with energies from 30 to 200 GeV) was also extracted: \( |v - v_\mu|/v_\mu \lesssim 4 \times 10^{-5} \) [3].

While urging the experimental community to further check and debate on these results, in particular the most recent ones, it is worth to explore which theoretical consequences would follow from the hypothesis that the muon neutrino is a superluminal particle.

This clearly requires a deep modification of the Standard Model (SM) of particle physics, that assumes particles to be subluminal. The energy and momentum of a subluminal particle of mass m and velocity \( \vec{v} \) are \( E = mc^2/\sqrt{1 - \vec{v}^2/c^2} \), \( \vec{p} = m\vec{v}/\sqrt{1 - \vec{v}^2/c^2} \). They are related by the dispersion relation \( E^2 = p^2 c^2 + m^2 c^4 \), where \( p = |\vec{p}| \), and the deviation from the speed of light is

\[ \frac{c - v}{c} = \frac{c}{c + v} \left( \frac{mc^2}{E} \right)^2. \] (2)

Here we focus on two possibilities to account for a superluminal particle: the tachyon [4] and the Coleman-Glashow particle [5,6].

The usual expressions for energy and momentum can be extended to the region \( v > c \) provided we substitute in the numerator \( m \to \tilde{m} \), where \( \tilde{m} \) is a real number. For such a particle, the energy and momentum are thus \( E = \tilde{m} c^2/\sqrt{\tilde{v}^2/c^2 - 1} \), \( \vec{p} = \tilde{m} \vec{v}/\sqrt{\tilde{v}^2/c^2 - 1} \), and satisfy the dispersion relation

\[ E^2 = p^2 c^2 - \tilde{m}^2 c^4. \] (3)

A tachyonic particle of mass \( \tilde{m} c^2 \) and energy E then travels faster than c by an amount

\[ \frac{v - c}{c} = \frac{c}{c + v} \left( \frac{\tilde{m} c^2}{E} \right)^2. \] (4)

The deviation from the speed of light for a tachyon is thus opposite with respect to the one of a subluminal
particle with the same mass, eq. (2). In both cases, for energies much larger than the mass, the particle speed $v$ approaches $c$. We display in fig. 1 the relative speed of the tachyon with respect to light as a function of the tachyon mass and for selected energy values.

The proposal that the neutrino could be a tachyon dates back to 1985 [7]. In the light of the recent results, it is worth to consider this hypothesis as a possible explanation of the OPERA data. As we are going to discuss, this interpretation is very problematic for various reasons: not only the deviation from $c$ would depend on energy, but it would not even be possible for a pion to produce a tachyon with the mass in the range required to fit the OPERA data.

Another proposal to account for a superluminal particle has been suggested by Coleman and Glashow (CG) [5,6]. The idea is that the $i$-th particle has, in addition to its own mass $m_i$, its own maximum attainable velocity $c_i$, and obeys the standard dispersion relation

$$E_i^2 = p_i^2 c_i^2 + m_i^2 c_i^4. \quad (5)$$

The CG muon neutrino can indeed account for the OPERA data without any trouble associated with its production from pion. To explain the observation of neutrinos associated in time with SN1987a, it is however necessary to introduce another neutrino with speed practically equal to $c$. This brings severe problems to neutrino oscillations, so that even the CG muon neutrino appears not to be a fully satisfactory explanation.

We draw our conclusions in the last section.

**Problems of a tachyonic interpretation.**

**Energy independence of the early arrival times.** If the neutrinos produced at CERN are tachyons with mass $\tilde{m}$, after having travelled a distance $L \approx 730$ km, their associated early arrival time is

$$\delta t = \frac{L}{c} \frac{v-c}{c},$$

with $\frac{L}{c} \approx 2.4 \text{ ms}$. Consider two tachyonic neutrino beams of energy $E_1$ and $E_2$, with $E_1 \leq E_2$ for definiteness. As follows from eq. (4), the ratio of their early arrival times $\delta t_1$ and $\delta t_2$ has a simple energy scaling:

$$\frac{\delta t_1}{\delta t_2} \approx \frac{E_2}{E_1}^2. \quad (6)$$

The early arrival time of a tachyon neutrino beam is indeed smaller the larger is its energy. In particular, for $E_2 \approx 3E_1$, one expects $\delta t_2 \approx \delta t_1/9$. The difference of the arrival times is thus negative: $\delta t_2 - \delta t_1 \approx -\delta t_1$.

Now, the OPERA Collaborations considers two sample neutrino beams with mean energy equal to $E_1 = 13.9 \text{ GeV}$ and $E_2 = 42.9 \text{ GeV}$, respectively\(^1\). The ratio of these energies is indeed close to 3. However, the experimental values of the associated early arrival times are, respectively, $\delta t_1 = (53.1 \pm 18.8 \text{ (stat)} \pm 7.4 \text{ (sys)}) \text{ ns}$ and $\delta t_2 = (67.1 \pm 18.2 \text{ (stat)} \pm 7.4 \text{ (sys)}) \text{ ns}$. These data display no evidence of an energy dependence. OPERA quotes a value $\delta t_2 - \delta t_1 = (14.0 \pm 26.2) \text{ ns}$ for the difference of the arrival times $\delta t_2 - \delta t_1$. Far from being close to $-\delta t_1$ as expected for a tachyon, the latter value is even slightly positive, although consistent with zero.

This simple argument disfavors the tachyon explanation of the OPERA data. The same conclusions were drawn in refs. [8,9] (appeared when this paper was completed), carrying out a detailed numerical analysis and including in the fit not only the recent OPERA data but also the Fermilab data, which do not display any energy dependence too.

One could however still question this conclusion, since the energies $E_1 = 13.9 \text{ GeV}$ and $E_2 = 42.9 \text{ GeV}$ quoted by OPERA are mean ones and if we consider the 3σ range associated to $\delta t_2 - \delta t_1$ we find the interval $[-65, 93]$ ns.

**Tachyon mass range from OPERA.** Suppose that we close an eye on the energy dependence and we stick to the interpretation of the OPERA early arrival time in terms of a tachyonic muon neutrino. As we are going to discuss, arguments based solely on kinematics allow to obtain an indication for the value of the tachyonic muon neutrino mass.

In terms of the muon neutrino energy $E$ and the muon neutrino velocity $v$, the tachyonic muon neutrino mass $\tilde{m}$ is simply given by (see eq. (4)):

$$\tilde{m}c^2 \approx \sqrt{\frac{2}{c} \frac{v-c}{c} E}. \quad (7)$$

Since OPERA deals with neutrinos with mean energy $\langle E \rangle = 17 \text{ GeV}$ and observes $(v-c)/c = (2.48 \pm 0.28 \pm 0.30) \times 10^{-5}$, the corresponding tachyonic mass value is $\tilde{m}c^2 = (110-130) \text{ MeV}$ at $1 \sigma$, and $(85-146) \text{ MeV}$ at $3 \sigma$ (statistical and systematic errors are

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\(^1\)If neutrinos were tachyons, the energy reconstruction of the OPERA Collaboration should be revisited. However, for tachyonic masses smaller than GeV, such effect is negligible for the sake of the present considerations.
Superluminal neutrinos

Fig. 2: (Colour on-line) Kinematics for $\pi \rightarrow \mu \nu_\mu$ assuming that the muon neutrino is a tachyon (T) or a bradyon (B). The muon neutrino energy $E_{\nu_\mu}$ (solid), the muon energy $E_\mu$ (dotted-dashed) and the associated momentum (dashed) are shown as a function of the muon neutrino mass.

the muon energy and momentum allow only a small tachyonic mass, say smaller than about 10 MeV/c\(^2\). When inserted in eq. (4) and keeping the muon neutrino energy $E = 17$ GeV, the bound $\bar{m} \leq 10$ MeV/c\(^2\) would imply $(v - c)/c \leq 1.7 \times 10^{-7}$, which corresponds to an early arrival time at OPERA of $\delta t \leq 0.6$ ns. This is at least two orders of magnitude below the observed value.

We can rephrase all this also in another way: To end up with $(v - c)/c \approx 2 \times 10^{-5}$ while keeping $\bar{m} = 10$ MeV/c\(^2\), a muon neutrino beam energy $E \approx 1.4$ GeV would have been necessary. The latter value seems to be definitely too small with respect to the reconstructed muon neutrino energy. We conclude that the tachyonic explanation of the early arrival times of muon neutrinos at OPERA is ruled out.

We also note that a kinematical analysis of muon decay ($\mu \rightarrow e\bar{\nu}_e\nu_\mu$) using the tachyonic mass range suggested by OPERA would produce serious difficulties. For simplicity, consider that $\nu_\mu$ has a tachyonic mass $\bar{m}$ while $e$ and $\bar{\nu}_e$ are massless. Then, in the corner of the phase space where $E_{\nu_\mu} = 0$ (and consequently $p_{\nu_\mu} = m_\mu c$), the electron energy can be as high as $E_e \leq m_\mu c^2/2(1 + \bar{m}/m_\mu)$ (intuitively, $e$ and $\bar{\nu}_e$ have to balance the large momentum of the tachyon, and they have a lot of energy to do so, since the tachyon energy is zero). Even more significantly, one can see that for every value of the allowed energy range for the tachyon, $0 \leq E_{\nu_\mu} \leq m_\mu c^2/2(1 + \bar{m}/m_\mu)$, the maximum value of $E_e$ is larger than $m_\mu c^2/2(1 + \bar{m}/m_\mu)$. In conclusion, values of $\bar{m} > 10$ MeV/c\(^2\) would be immediately detectable in the electron spectrum, whose endpoint would be much larger than $m_\mu/2$. Once again, this argument rules out the hypothesis that the OPERA muon neutrino is a tachyon.

Supernova SN1987a requires $a \lesssim eV$ electron-neutrino.

Let us suppose that we close another eye on the problems associated with the production of a beam of tachyonic muon neutrinos with 100 MeV mass and persevere on this road. Can we agree with the SN1987a data? As we are going to discuss this is possible.

The SN1987a is $L = 1.68 \times 10^{57}$ ly far from the Earth and exploded releasing a huge neutrino signal, with typical energies 10–20 MeV, which allowed the first direct detection of astrophysical neutrinos. All neutrino flavors were emitted but Kamiokande-II, IMB and Baksan were designed to detect mainly electron antineutrinos. The signal lasted about 10 s and the photons also arrived within a few hours. See for instance ref. [10] for a recent review and a list of references.

The advance (delay) of a tachyonic (bradyonic) antineutrino with respect to light is $\delta T = T |v - c|/c$, where $T = L/c$ is the time associated to the photon trip from SN1987a to the Earth\(^4\). The fact that photons and electron antineutrinos arrived within few hours implies that

\(^2\) Clearly this value is just a rough estimate, due to the significant energy spread of the neutrino beam, but we said that we ignore this as it would also cause an energy dependence of the early arrival time.

\(^3\) A proton beam of 400 GeV/c from SPS hits a graphite target producing pions which are focused by two magnetic horns and directed towards the tunnel.

\(^4\) The SN exploded when the Earth was in the quaternary period and on such timescales the effects due to the expansion of the universe can be neglected.
\[ \delta T/T = |v - c|/c \sim 10^{-9}, \] which in turn translates into an upper bound for the (bradyonic or tachyonic) mass of the electron antineutrino of about 1 keV.

Electron antineutrinos arrived with a time spread \( \Delta T \lesssim 10\) s, as indicated by observations. This poses a much tighter limit on their (tachyonic or bradyonic) mass \( m_{\bar{\nu}_e} \) than the one just discussed. The time spread \( \Delta T = |T_2 - T_1| \) of two neutrinos with energies \( E_1 \) and \( E_2 \) (with \( E_1 \leq E_2 \)) is

\[
\frac{\Delta T}{T} = \frac{m_{\bar{\nu}_e}^2}{2E_1^2} \left( 1 - \frac{E_1^2}{E_2^2} \right). \tag{9}
\]

For the numerical values mentioned above, one obtains \( m_{\bar{\nu}_e} \lesssim 40\) eV/c\(^2\). This limit, applies however to the electron antineutrino\(^5\).

The SN emits all neutrino flavors. Let us suppose that it emits also a 100 MeV tachyonic muon neutrino: its advance with respect to light would be of about \( 4 \) y, but with an enormous spread as can it be realized by considering eq. (9) in the case of a particle with mass bigger than its energy. These neutrinos would have certainly escaped detection.

**Oscillations: game over.** According to the picture emerged so far, the ratio between the tachyonic mass of the muon neutrino suggested by OPERA and the mass of the electron antineutrino suggested by SN1987a would be as large as \( 10^5 \). In principle, the formalism of neutrino oscillation in the tachyonic case is the same as for an ordinary neutrino [12], but it appears difficult to come to pact with the robust information coming from neutrino oscillation experiments. Indeed, these experiments put stringent bounds on the difference of neutrino masses squared: \( |\Delta m_{32}^2| \approx 2.4 \times 10^{-3} \) eV\(^2\) and \( |\Delta m_{21}^2| \approx 7.6 \times 10^{-5} \) eV\(^2\) [13].

Even though the analysis of the experimental data should be redone since the fluxes at the production in the Sun for electron antineutrinos and in the atmosphere for muon neutrinos would change, it seems hopeless to find an agreement with experimental data on oscillations.

**Muon neutrino à la Coleman-Glashow.** As an alternative scenario, consider now two CG neutrino mass eigenstates with masses \( \nu_1 \) and \( \nu_2 \) not larger than \( \mathcal{O}(eV)/c^2 \), with different limit speeds \( c_1 \) and \( c_2 \) [5,6]. One may infer \( |c_1 - c|/c \lesssim 10^{-9} \) from SN1987a as discussed in the previous section, while \( (c_2 - c)/c \approx 2.5 \times 10^{-5} \) as suggested by OPERA.

Let us suppose that \( \nu_2 \) has a significant mixing with the muon neutrino of the OPERA beam, and that \( \nu_1 \) mixes significantly with the electron neutrino. We now revisit for this CG superluminal neutrino model the same issues discussed for the tachyon.

First of all, the early arrival time of the muon neutrino beam is energy independent, since now \( c_2 \) is a constant (already chosen to reproduce the results from OPERA)

\[ m_{\nu_2} \lesssim \mathcal{O}(eV); \] \[ m_{\nu_2} \lesssim \mathcal{O}(eV); \] with these assumptions the standard kinematics used for event reconstruction at OPERA need not be modified.

At first glance, one could envisage no problem for the production of such CG muon neutrino from pion decay. However, a careful kinematical analysis reveals that the situation should be considered in more details.

We first assume that \( c_\pi = c_\nu = c \). For the sake of the comparison with OPERA, the relevant configuration is the one in which the CG muon neutrino and the muon have negligible transverse momenta with respect to the pion momentum, so that the CG muon neutrino is actually emitted in the Gran Sasso direction. In this case, there is an upper bound for the CG muon neutrino energy (see also [14,15]):

\[
E_\nu \lesssim \frac{(m_{\nu_2}^2 - m_{\nu_1}^2)\epsilon c^4}{2E_\pi} \frac{c}{c_2 - c} \approx 3 \text{ GeV}, \tag{10}
\]

where the numerical value is obtained by considering \( E_\pi \sim 60 \) GeV, together with the OPERA result \( (c_2 - c)/c \approx 2.5 \times 10^{-5} \). Clearly, this bound is violated by OPERA, that detects muon neutrinos with energies much larger than this value.

A widely different scenario follows if one assumes \( c_\pi = c_\nu = c \). In this case the pion decay is forbidden unless the pion energy \( E_\pi \) is smaller than a threshold energy given by

\[
E_\pi \lesssim \left( \frac{(m_{\nu_2}^2 - m_{\nu_1}^2)\epsilon c^4}{2} \frac{c}{c_2 - c} \right)^{1/2} \approx 13 \text{ GeV}, \tag{11}
\]

where the OPERA result for \( (c_2 - c)/c \) has been used. Clearly, muon neutrinos should have \( E_\nu \lesssim E_\pi \). Again, this is in contrast with observation since the mean energy of the pions produced at CERN is about 60 GeV and OPERA detects neutrinos with energies up to about 80 GeV.

This discussion shows that the observed phenomenology depends critically on the actual values of the \( c_i \)'s of the three particles involved in pion decay, whose values have been recently reviewed in [15]. Since at this stage a discussion of all possibilities would be inconclusive, we do not elaborate further on this point.

As for the SN1987a, a beam of CG \( \nu_2 \) would pose no problem, because it would have simply arrived about 4 y in advance with respect to the photons and the other \( \nu_1 \)'s. Most probably it would have escaped detection since the detectors had a lower sensitivity to muon neutrinos (moreover Kamiokande-II started taking data only in 1985). At variance with the tachyon case, it is important to remark that the \( \nu_2 \) beam does not spread out in time but all the neutrinos arrive within a few seconds, because we assumed their mass to be smaller than \( eV/c^2 \).

A serious problem for CG neutrinos is again due to neutrino oscillations, as can be shown by using the formalism of refs. [5,6]. The two CG neutrino eigenstates

\[ m_{\nu_2} \lesssim \mathcal{O}(eV); \]

\[ m_{\nu_2} \lesssim \mathcal{O}(eV); \]
travel at different speeds and this affects the neutrino oscillation probability similarly to a difference in mass:

\[ P(\nu_L \rightarrow \nu_E) = 1 - \sin^2 2\theta \times \sin^2 \left( \frac{R}{\hbar c} \left( \frac{(m_E^2 - m_L^2) c^4}{4E} + \frac{\delta c}{c} E \right) \right), \tag{12} \]

where \( \theta \) is the mixing angle, \( R \) is the distance from source to detector, \( \bar{c} = \frac{c_1 + c_2}{2} \), \( \delta c = c_2 - c_1 \) and \( E \) is the neutrino energy, typically in the range of a few MeV for reactor and solar experiments. For numerical estimates, it is perfectly safe to replace \( \bar{c} \) with \( c \). Oscillation experiments (see for instance [16]) indicate a value for \( m_2^2 - m_1^2 \approx 10^{-3} \text{eV}^2 / c^4 \). This translates in a sensitivity \( \delta c / c \) of about \( 10^{-18} \), much smaller than what would be needed to explain the OPERA data. This can be seen as follows: the experimentally tolerated oscillation frequency is the one of the first term of the \( \sin^2 \) argument in eq. (12) with \( (m_2^2 - m_1^2) c^4 / 10^{-3} \text{eV}^2 / c^4 \). A comparable frequency would result from the second term of the argument of \( \sin^2 \) only if \( \delta c / c \approx 10^{-18} \). Also due to the different energy dependence of these two terms, it seems unlikely that a cancellation might be at work for a much larger value of \( \delta c / c \approx 10^{-5} \) in the energy range probed by oscillation experiments. A similar analysis was done in refs. [5,6], suggesting an even tighter limit \( \delta c / c \approx 6 \times 10^{-22} \).

In conclusion, also CG superluminal neutrinos seem not to provide a fully satisfactory explanation of the OPERA results.

**Conclusions.** – The evidence for muonic neutrinos traveling slightly faster than light is within the range as reported by the OPERA Collaboration, motivated us to explore two possible interpretations of the data: the hypothesis that the muon neutrino is a tachyon or that it is a Coleman-Glashow neutrino.

We demonstrated that the tachyonic interpretation is hardly reconciled with the energy independence of the OPERA data, as shown also by [8,9]. The real problem that we point out here is that it would be impossible to produce a 100 MeV tachyon from pion decay. The data associated with SN1987a can be interpreted by assuming an eV electron antineutrino. This picture however clashes with what is known concerning neutrino oscillations.

A Coleman-Glashow superluminal neutrino beam would presumably face problems with kinematics, but it is difficult to assess details here because the kinematic bounds strongly depend on the actual values of the limiting speeds of the particles involved in pion decay. A CG neutrino could be easily reconciled with SN1987a data but, on the other hand, it would be not possible to reconcile the model with neutrino oscillations.

In conclusion, the picture emerging from combining OPERA with other experimental data is that neutrinos should not obey a tachyon-type nor a Coleman-Glashow-type dispersion relation, but rather a dispersion relation with a very peculiar energy dependence [9,17]. Even in this case, a serious problem could be represented by energy losses due to electron positron pair production [18].

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