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# ARE MUON NEUTRINOS FASTER-THAN-LIGHT PARTICLES ? (COMMENTS ON A RECENT PAPER BY CHODOS *et al.*) (°)

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Running Head: Are muon neutrinos faster-than-light particles?
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Abstract - A paper [1] appeared recently, which is quite noticeable since it calls attention to interesting experimental results referring to the old-dated problem whether neutrinos are Superluminal (or not); but it disregards most of the previous theoretical literature. We complement it, therefore, from the theoretical (and "historical") point of view, and add some experimental predictions. Analogously, a very recent related paper by Van Dam *et al.* is briefly commented upon, on the basis of the already existing theoretical approaches.

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In a recent paper by Chodos et al.[1] attention has been called to five experimental articles[2] indicating that the muon neutrino coming from pion decay may carry a negative fourmomentum-square; in the sense that four of those papers seem to favour such a conclusion. The experimental data analysed by Chodos et al. are certainly worth of further experimental check. Particularly interesting is the "Note added" at page 434 of ref.[1] (a note, incidentally, that came to our attention only now), in which those authors claim the world average for the fourmomentum-square carried by the muon neutrino produced in the decay $\pi^+ \to \mu^+ + \nu$ to be, with the metric-signature (+ - - -),

$$p^2 \equiv p_\alpha p^\alpha = (-0.0166 \pm 0.091)\ \mathrm{MeV}^2/c^2 \ , \qquad (1)$$

this fact suggesting of course (even if by two standard deviations only) that such neutrinos $\nu$ be tachyonic.

The idea —however— that neutrinos can be tachyons, at least in some cases, has a long story, related to a theoretical background that does not show up in ref.[1]. We want therefore to complement briefly the "introduction" to eq.(1) appeared therein, from the theoretical (and "historical") point of view; and add some experimental predictions. Incidentally, let us recall that the issue of tachyons —although unconventional— already attracted about $10^3$ publications, six hundred of which can be found quoted in [3]; cf. also the references cited in the old review-article [3], in the book [4], and in [6].

(i) Let us premise that a little of theory shows ($c=1$) the relation $p^2 \equiv p_\alpha p^\alpha \equiv E^2 - \vec{p}^2 = +m_o^2 > 0$ to hold only for bradyons (slower-than-light particles), whilst for tachyons it generalizes into $p^2 = -m_o^2 < 0$. Analogously, for $V^2 > 1$, it holds $m = m_o/\sqrt{V^2-1}$. In the case of tachyons, therefore, it is negative the fourmomentum-square $p^2$, rather than the square of the proper-mass $m_o$ (which can be regarded as real). For a modern view on tachyons see e.g. the recent review-paper [3], to appear also as [7], and the papers [9÷12].

(ii) Moreover, since an ordinary Lorentz transformation may carry a positive-energy tachyon T (travelling forward in time) into a "negative-energy tachyon T' travelling backwards in time", it is necessary to introduce —as the Third Postulate of Special Relativity[9,13]— the Stückelberg-Feynman switching procedure (also known as "reinterpretation rule") in order to reinterpret T' as the antiparticle $\overline{T}$ of T: so that $T' \equiv \overline{T}$, object $\overline{T}$ being obviously endowed with positive energy and motion forward in time. The first application of the "switching" appeared in [14]. As a consequence, if $\nu$ is a tachyon neutrino with velocity $\vec{V}$ in the pion rest-frame, then an observer O' travelling with respect to the pion with (subluminal) velocity $\vec{u}$ such that $\vec{u}\cdot\vec{V} > 1$ will not see the decay $\pi \to \mu + \nu$, but the process [15]

$$\pi + \bar{\nu} \to \mu \ , \tag{2}$$

with the experimental consequences exploited below (see point (iv)). Let us recall here that a complete resolution in microphysics of the so-called tachyon causal problems is to be found in [9,3].

(iii) Coming to the main point, the natural idea that neutrinos could be Superluminal started to be common among the tachyon theorists in Europe (Milan, Catania, Rome, Palermo, Pisa, Ljubljana, Kiev, etc.) since the late Sixties. One of us has been "propaganding" such a possibility in a number of seminars, and even university lectures, since that time ( ~ 1968); early mentions of it being due also to Cawley [16] and Edmonds [16]. For instance, when eventually publishing in 1980 <u>detailed</u> kinematical calculations for the processes of: (A) tachyon absorption, (B) tachyon emission, and (C) tachyon exchange between two ordinary particles, Maccarrone and Recami warned (at p.99 of [15]; cf. also p.110 of [3], and p.506 of [10]) that in the center-of-mass of the decay $\pi \to \mu + \nu$, in which $|\vec{p}|_{\mu} = |\vec{p}|_{\nu}$, it results that:

$$|\vec{p}|_{\nu} \simeq 29.788995 \text{ MeV/c} \equiv |\vec{p}|_{o} \quad \text{if} \quad m_{\nu} = 0; \quad v_{\nu} = c \tag{3a}$$

in the case that $\nu$ is a "luxon"; whilst:

$$|\vec{p}|_{\nu} < |\vec{p}|_{o} \quad \text{if} \quad m_{\nu} \neq 0; \quad v_{\nu} < c \tag{3b}$$

in the case that $\nu$ is a bradyon; and:

$$|\vec{p}|_{\nu} > |\vec{p}|_{o} \quad \text{if} \quad m_{\nu} \neq 0; \quad v_{\nu} > c \tag{3c}$$

in the case that $\nu$ is a tachyon. Quantities $m_{\nu}$ and $v_{\nu}$ are the muon-neutrino proper-mass and speed, respectively. In particular, for a <u>bradyonic</u> neutrino with $m_{\nu} = 0.5$ MeV/c$^2$ one would get [17]: $|\vec{p}|_{\nu} \simeq 29.785695$ MeV/c; <u>but</u>, by using eqs.(1'),(2) in [15], for a <u>tachyonic</u> neutrino with the <u>same</u> proper-mass $m_{\nu} = 0.5$ MeV/c$^2$ one gets: $|\vec{p}|_{\nu} \simeq 29.792296$ MeV/c. The most recent experimental data appear compatible with a tachyon-neutrino with $m_{\nu} \simeq 0.46$ MeV/c$^2$:

$$|\vec{p}|_{\nu} \simeq 29.791789 \text{ MeV/c} \quad \text{if} \quad m_{\nu} \simeq 0.46 \text{ MeV/c}^2 \quad \text{with} \quad v_{\nu} > c, \tag{4}$$

as it follows from the mentioned eq.(1') in ref.[15]:

$$2m_\pi |\vec{p}|_t = \left[(m_t^2 + m_\mu^2 - m_\pi^2)^2 + 4m_t^2 m_\pi^2\right]^{\frac{1}{2}} , \tag{5}$$

where we wrote t instead of ν. By the further eq.(1") in ref.[15]:

$$V^2 = 1 + 4m_t^2 m_\pi^2 / (m_t^2 + m_\mu^2 - m_\pi^2)^2 , \tag{6}$$

we get that the case in our eq.(4) corresponds to a Superluminal speed $[V \equiv v_\nu]$:

$$V/c \simeq 1.00012 .$$

In a generic (subluminal) frame f, in which $P^\alpha$ and $p^\alpha$ are the pion and neutrino fourmomentum, respectively, we would get[15]:

$$\begin{cases} m_\pi^2 - m_\mu^2 = 2p_\alpha P^\alpha - m_\nu^2 & \text{in the bradyon case;} \\ \phantom{m_\pi^2 - m_\mu^2} = 2p_\alpha P^\alpha & \text{in the luxon case;} \\ \phantom{m_\pi^2 - m_\mu^2} = 2p_\alpha P^\alpha + m_\nu^2 & \text{in the tachyon case.} \end{cases} \tag{7}$$

Before going on, let us also remind the reader that[15]: (a) an ordinary particle A cannot emit in its rest-frame any tachyon T (whatever be the tachyon proper-mass m), unless the rest-mass M of A jumps to a lower value M' such that $M^2 - M'^2 = m^2 + 2ME_T$, with $E_T \equiv \sqrt{\vec{p}^2 - m^2}$ and m a positive real quantity; in a generic frame it being $M^2 - M'^2 = m^2 + 2p_\alpha P^\alpha$. On the contrary: (b) an ordinary particle A at rest can a priori absorb (suitable) tachyons both when increasing or conserving its rest-mass, and when lowering it: in fact $M^2 - M'^2 = m^2 - 2ME_T$; and, in a generic (subluminal) frame f, it is $M^2 - M'^2 = m^2 - 2p_\alpha P^\alpha$.

Let us observe —especially in connection with eqs.(7)— that quantity $p_\alpha P^\alpha$ is a Lorentz-invariant, even if it depends on the nature of the muon-neutrino.

(iv) Let us go back to the consideration at the end of point (ii) above, assuming for prudence's sake that $m_\nu \equiv m_t \simeq 0.4$ MeV/$c^2$, so that in the pion rest-frame $v_\nu \equiv V \simeq 1.00009\,c$. If we analyse the decay into muons of pions in flight, we shall start to observe processes of the type (2), besides the ordinary decays $\pi \to \mu + \nu$, when the pion speed in the lab is $v_\pi > c^2/V \simeq 0.99991\,c$. Let us for instance take pions with a lab energy $E_\pi \simeq 31.2$ GeV, so that $v_\pi \simeq 0.99999\,c$; in such a condition, due to Lorentz dilation, the pion mean-life will be $\Delta\tau' = \gamma \cdot \Delta\tau_o \simeq 5.82 \times 10^{-6}$ s. But the ordinary decays in flight will appear in the lab as processes (2), i.e. as processes $\pi+\bar{\nu}\rightarrow\mu$, whenever $\vec{v}_{\pi}\cdot\vec{V}>c^2$. Some trivial geometry tells us, therefore, that one "decay" event out of ~24955 decays will actually appear in the lab as a tachyon-absorption process (2); which corresponds, for the "partial mode" (2), to a mean-life in flight of

$$\Delta\tau'(\pi+\nu\rightarrow\mu) = \Delta\tau'\cdot R \simeq 0.14525 \text{ s} \ , \qquad (8)$$

R being the mentioned geometrical factor, $R\simeq 2.49545\times 10^4$.

In the case $m_{\nu}\equiv m_t \simeq 0.46$ MeV/$c^2$, we would have got the partial mean-life $\Delta\tau'(\pi+\nu\rightarrow\mu) \simeq 0.11648$ s, corresponding to one positive event out of 20014 decays.

Of course, if the muon-neutrino is Superluminal, the mean-life $\Delta\tau_o$ of the pion at rest is connected —via a Lorentz transformation— with the $\pi$-$\bar{\nu}$ cross-section times the $\bar{\nu}$ "cosmic flux": see e.g. [18]. If electron-neutrinos coming from the neutron decay were Superluminal too, then interesting analogous considerations could be developed with regard to the neutron mean-life; and so on.

In relation to the fact that an "intrinsic" (rest-frame) tachyon emission can appear as an antitachyon absorption in another suitable frame f, let us finally report here the following two clarifying theorems [9,3,15]:

Theorem I: « Necessary and sufficient condition for a process, observed either as the emission or as the absorption of a tachyon T by a bradyon A, to be a tachyon-emission in the A rest-frame —i.e., to be an "intrinsic emission"— is that during the process A lowers its rest-mass (invariant statement!) in such a way that $m_T^2 < \Delta M^2 < M_i^2$ », where: $m_T$ is the tachyon proper-mass; $\Delta M^2 \equiv M_i^2 - M_f^2$; and $M_i$, $M_f$ are the bradyon initial and final rest-mass, respectively;

Theorem II: «Necessary and sufficient condition for a process, observed either as the emission or as the absorption of a tachyon T by a bradyon A, to be a tachyon-absorption in the A rest-frame —i.e., to be an intrinsic absorption— is that $-\infty < \Delta M^2 < m_T^2$ ». Notice that $\Delta M^2 \equiv \Delta(M^2)$ can be both positive and negative.

(v) To complement what reported under point (iii) above, let us moreover mention that in 1976 Mignani and Recami [19] (see also p.91 in [3], and p.507 in [10]) observed, while considering e.g. the possible classical vacuum decays into tachyons, that: (a) the tachyon cosmic flux is expected to be close to that of neutrinos; (b) the tachyon cosmic flux is expected to have a Lorentz-invariant fourmomentum distribution, so that the large majority of "cosmic" tachyons ought to appear to every observer as endowed with speed very close to that of light ([19,3,10]; see also [20]).

(vi) As to the spin of tachyons, let us notice that —if the muon neutrinos from pion decay are Superluminal— the usual Spin-Statistics Theorem, holding for bradyons, appears to hold also for tachyons, so as maintained by Sudarshan et al.[21], even if contrary opinions were expressed[22].

In ref.[1], actually, Chodos et al. wrote down and studied a Dirac-type equation for tachyon fermions. Concerning this point, let us stress that investigations of such an equation are not new in the literature: we call the reader's attention, e.g., to the papers listed in [23].

The approach in [1] has been criticized by Van Dam et al.[24], on the basis of the wellknown fact[25] that, among the unitary representations of the Poincaré Group, no finite-dimensional representations exist in correspondence with $p^2 < 0$, except for the trivial (spin-zero) one. This fact has been a problem for tachyons since long. However, there are reasons for tachyons (reasons summarized e.g. in Sects.5, 9 and 11 of ref.[3]: see for instance Sect.5.17 therein; see also [26]) just to choose non-unitary representations in the space-like case. Unless one decides to modify the (Hilbert) state-space[27]. And, by resorting to the non-unitary representations for space-like objects, also tachyons can be associated with ordinary integer or semi-integer spins. We limit ourselves, here, to quote the related literature, listed in [28].

(vii) Two last remarks. According to the "duality principle"[4,3], if the existence of tachyon-neutrinos is confirmed, there should exist both tachyonic and bradyonic neutrinos: even if they will behave differently (see e.g. [29]).

According to one of the existing theoretical approaches[30], an interesting link exists between tachyons and magnetic monopoles, in the sense —for instance— that Superluminal electric charges would contribute to the field equations just as expected from magnetic monopoles[4,3,30]. Therefore, if a particle in its bradyonic state carries an electric charge (or dipole), then in the tachyonic state it ought to appear to carry a (Superluminal!) magnetic pole (dipole).

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