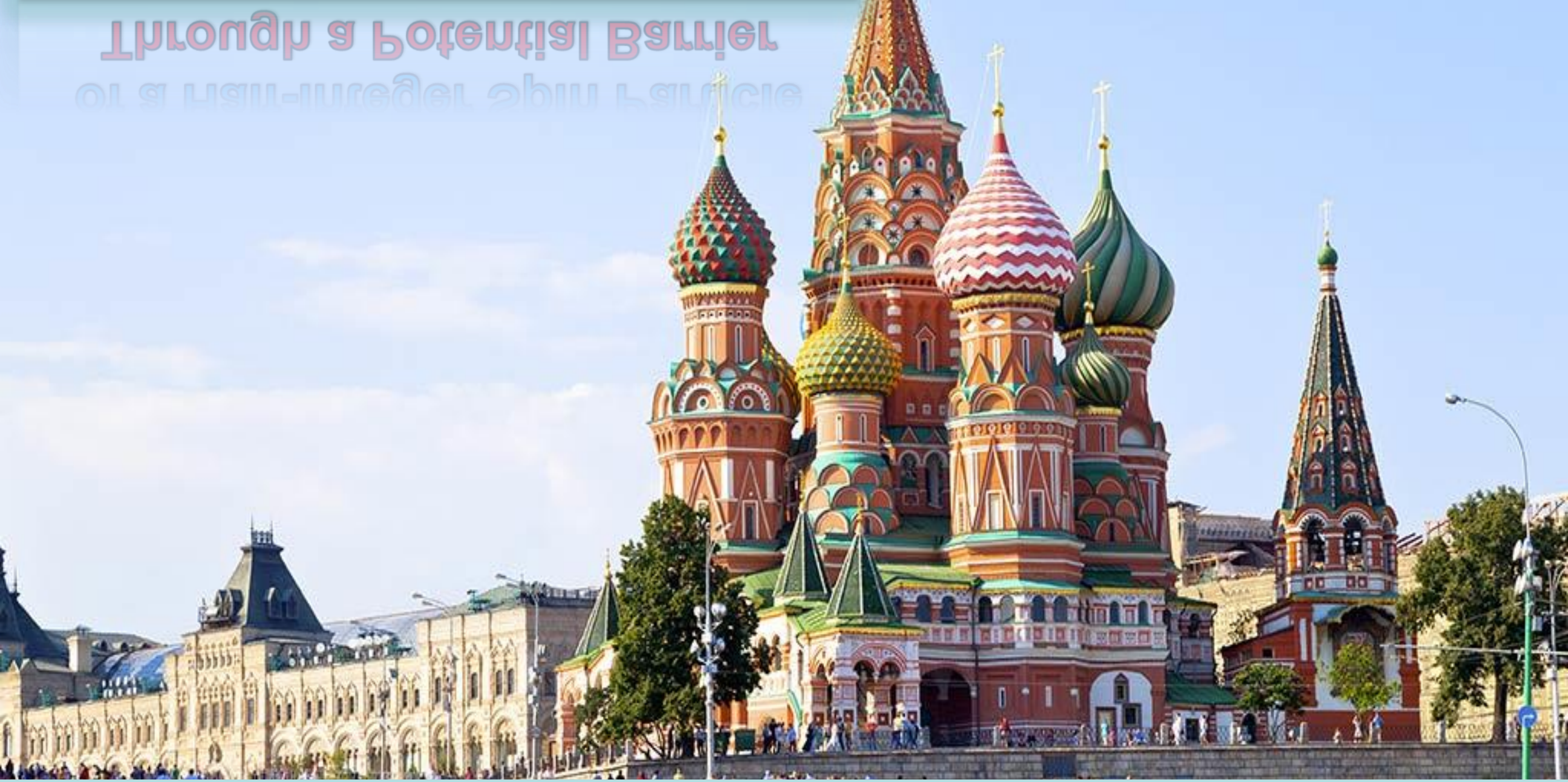
Superluminal Tunneling of a Half-Integer Spin Particle Through a Potential Barrier



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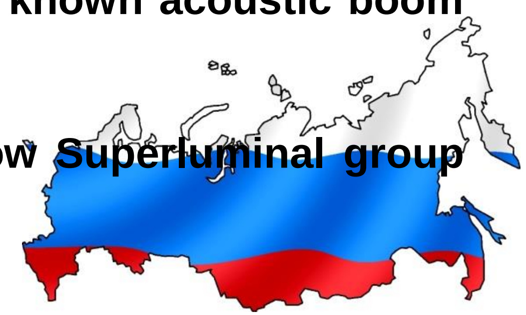
Why Does Physics Should Be Interested on Superluminal Phenomena?

The Einstein Theory of Relativity Forbids to Waves and Objects to Overcome the Speed of Light. The Universe is Made *(solely)* **of** ***Bradyons*** **and** ***Luxons***

Surdashan, Feinberg, Recami and others Extended the Theory of Relativity to Superluminal Phenomena Without Compromising its Foundations. The Universe is Made of ***Bradyons*****,** ***Luxons*** **and** *(Could Be)***Tachyons (*****at Least as Intermediate States*****) [1-2]**

A Glance at the Experimental Status of the Art

- **Neutrinos: experiments started in 1971 seems to show that muon-neutrinos and electron-neutrinos have an imaginary mass (***not yet confirmed***)**
- **Quasars:** ***apparent*** **Superluminal expansions observed in the core of Quasars show an initially** *Optical Boom* **phase similar to the well known acoustic boom (***accepted by the majority of the Astrophysicists***)**
- **Photonics: tunneling photons as** *evanescent waves* **show Superluminal group velocities (***confirmed***)**



Superluminal Tunneling:
a Prerogative for Photons Only?

Photonics is the best *place* to investigate Superluminal phenomena, both from theoretical and experimental perspective. For tunneling photons the theory predicts the *Hartmann Effect* **(both** *normal* **and** *extended***) that experiments confirm. [3]**

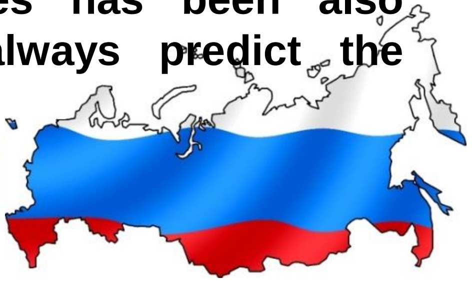
Does quantum theory predict Hartmann Effect also for tunneling (massive) particles?

- **Schrödinger Equation in presence of a potential barrier is mathematically identical to the Helmholtz Equation** *(the barrier height U greater then the particle energy E corresponds, for a given frequency, to a waveguide of transvers size)***:**

$$\nabla^2 f + k^2 f = 0 \quad \equiv \quad \nabla^2 \Psi + K^2 \Psi = 0 \quad ; \quad k = \frac{\omega}{c} \ and \ K = \frac{\sqrt{2m(E-V)}}{\hbar}$$

Quantum Tunneling leads to *Hartmann Effect* **also for a massive non-relativistic particles** *(theoretical prediction)***.**

- **In relativistic regime the Tunneling of massive particles has been also investigated through the Dirac Equation. The theory always predict the occurrence of** *Hartmann Effect***. [4]**



How Long Does it Take a Particle to Tunnel Through a Potential Barrier?

Hartmann Effect **may be predicted on the basis of the time spent by the particle inside the barrier. But:**

How to define the Tunneling Time for a quantum particle?

Unlike photons, a corpuscular picture of tunneling can not be realized because of the lack of a direct classical limit for the trajectories and velocities of the tunneling particle! Furthermore, no Hermitian operator is associated with it! [5-7]

…Dwell Time, Phase Time, Larmor Time, Landauer Time…

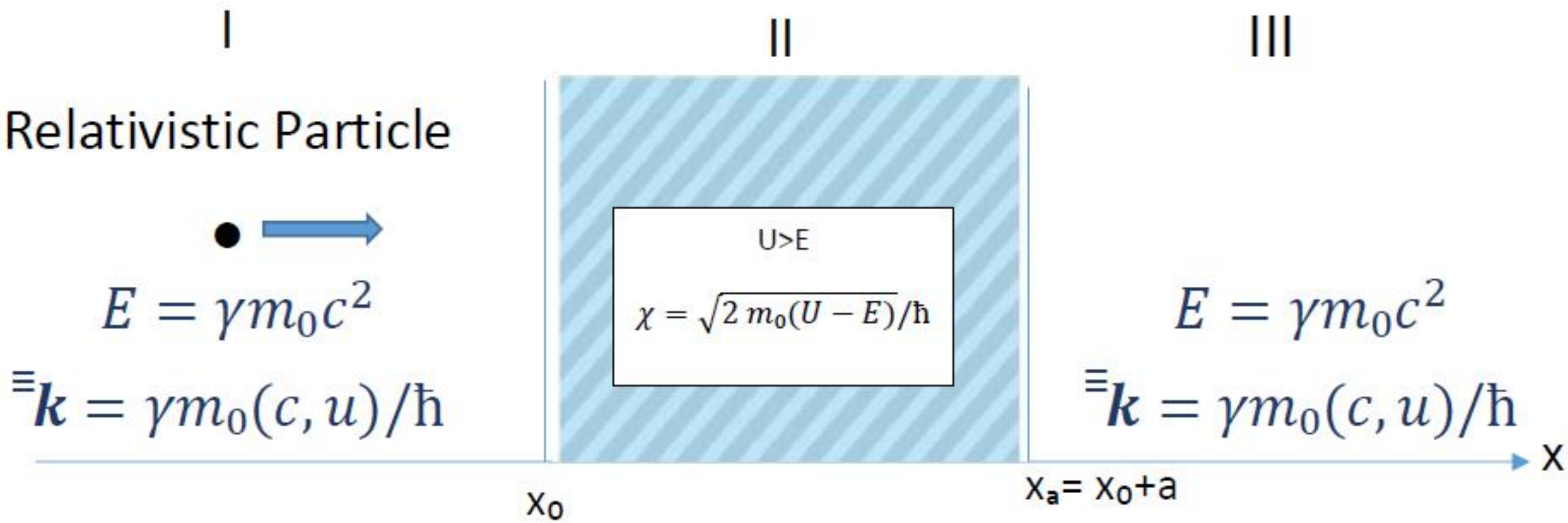
Till date there is not a clear consensus about Operational Definition of these times!

In the present work will be used the *Phase Time* **(asymptotic, non local), defined as [8]:**

"the difference between the time at which the peak of the transmitted packet leaves the barrier and the time at which the peak of the incident quasi-monochromatic wave packet arrives at the barrier"

This operational definition fits with the model used for the present study, which consists in a *monochromatic De Broglie* **wave that behaves like a** *confined evanescent waves* **inside the barrier.**

The Model:
Relativistic ½-Spin Particle Impinging a 1D Potential Barrier



$$\begin{cases} |\Psi\rangle_+ = \boldsymbol{N}\begin{pmatrix} 1 \\ \dfrac{cp_x}{E + m_0c^2} \end{pmatrix} exp\{i(k_0ct - k_xx)\} = \boldsymbol{N}\begin{pmatrix} 1 \\ \beta \end{pmatrix} exp\{i(k_0ct - k_xx)\} \\ |\Psi\rangle_- = \boldsymbol{N}\begin{pmatrix} -\dfrac{cp_x}{E + m_0c^2} \\ 1 \end{pmatrix} exp\{-i(k_0ct - k_xx)\} = \boldsymbol{N}\begin{pmatrix} -\beta \\ 1 \end{pmatrix} exp\{-i(k_0ct - k_xx)\} \end{cases}$$

$$\begin{cases} k_0 = \dfrac{p_0}{\hbar} = \dfrac{\gamma m_0 c}{\hbar} \\ k_x = \dfrac{p_x}{\hbar} = \dfrac{\gamma m_0 u}{\hbar} \end{cases}$$

Phase Time from the Transmitted Amplitude: Particle States

Continuity Conditions at the boundaries of the potential barrier (first Spinor component)

$$\begin{cases} \Psi(I)|_{x_0} = \varphi(II)|_{x_0} \\ \Psi(III)|_{x_0+a} = \varphi(II)|_{x_0+a} \\ \Psi'(I)|_{x_0} = \varphi'(II)|_{x_0} \\ \Psi'(III)|_{x_0+a} = \varphi'(II)|_{x_0+a} \end{cases}$$

$$\begin{cases} \Psi(I) = exp\{i(k_0ct - k_xx)\} + c_R exp\{-i(k_0ct - k_xx)\} \\ \varphi(II) = \alpha e^{\chi x} + \delta e^{-\chi x} \\ \Psi(III) = c_T exp\{i(k_0ct - k_xx)\} \end{cases}$$

$$\chi_+ = \frac{\sqrt{2m_0(U-E)}}{\hbar} \qquad Particle$$

Hypothesis: *a) the barrier must be large enough*
b) within the barrier the bi-spinor is time-independent, being a confined evanescent wave vector

from which is obtained the Transmitted Amplitude

$$c_T = \frac{4i\chi\Delta k}{exp\{i(k_0ct_a - k_xx_a)\}[e^{\chi x_a}(\chi - i\Delta k)^2 + e^{-\chi x_a}(\Delta k - i\chi)^2]}$$

and then the Phase Time

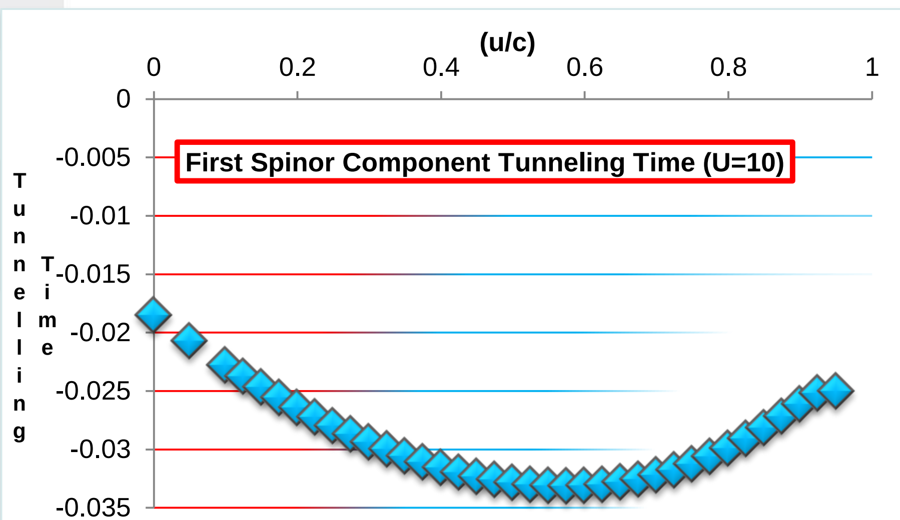
$$\tau = \hbar\frac{\partial arg\{C_T exp[i(k_0ct_a - k_xx_a)]\}}{\partial E}$$

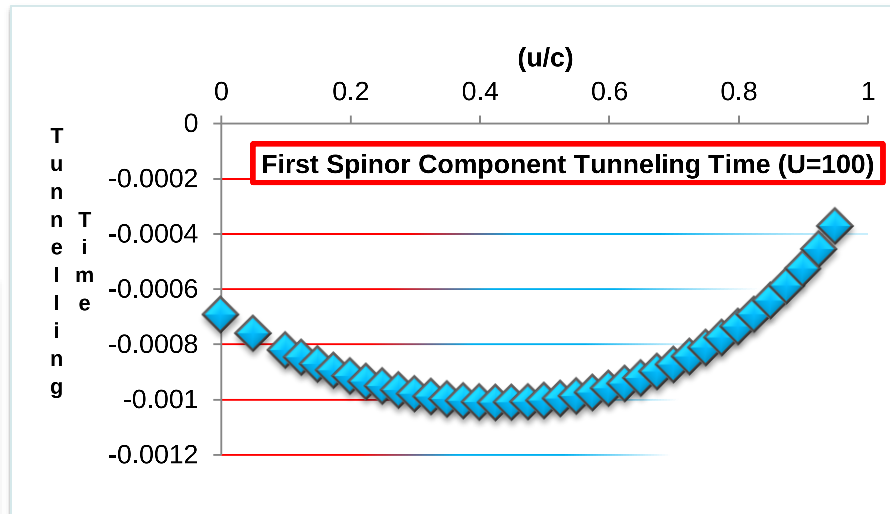
Phase Time: Superluminality for Particle States

First Spinor Component Tunneling Time for Particle States

$$\tau^{(1°)} = \frac{2m_0 \Delta k E(1-2\chi^2) + 2\hbar^2\chi^2\Delta k(2\Delta k^2 - 1)}{\hbar\chi E[(\Delta k^2 + \chi^2)^2 + 4\Delta k^2 \chi^2]}$$

Setting: $m_0 \equiv c \equiv \hbar = 1$





It must be recall that

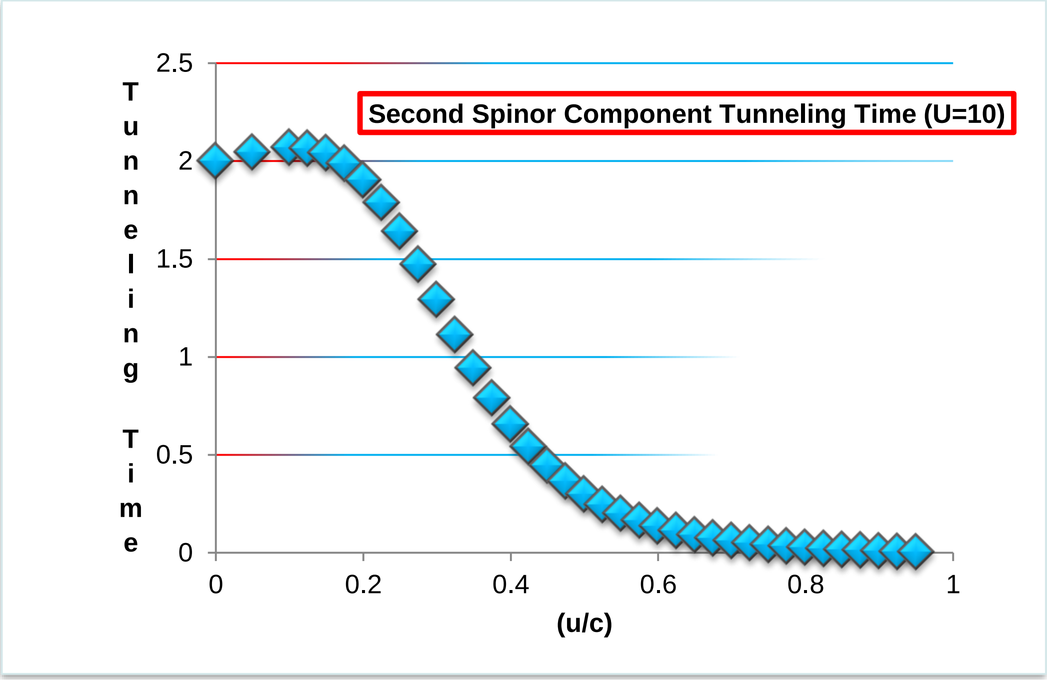
$$\begin{cases} \lim\limits_{U\to\infty} C_T^2 = 0 \\ \lim\limits_{U\to E} C_T^2 = 1 \end{cases}$$

Phase Time: Superluminality for Particle States

Second Spinor Component Tunneling Time for Particle States

$$\tau^{(2^\circ)} = \hbar \frac{2(1-\beta^2)(\Delta k^2 + \chi^2)}{E[(\Delta k^2 + \chi^2)^2 + 4\beta^4 \Delta k^2 \chi^2]} + \tau^{(1^\circ)}$$

Setting: $m_0 \equiv c \equiv \hbar = 1$



It must be recall that

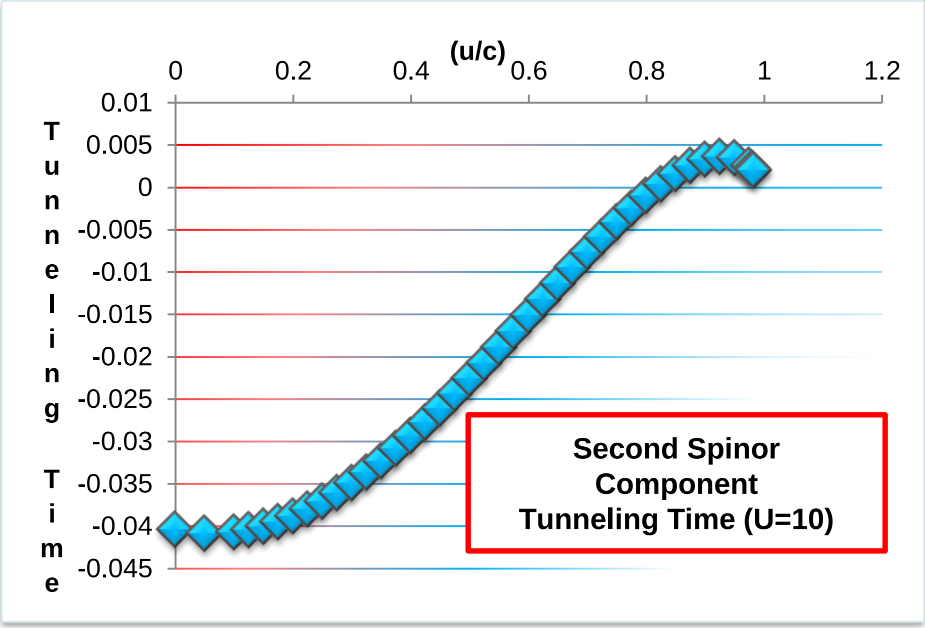
$$\begin{cases} \lim_{U\to\infty} C_T^2 = 0 \\ \lim_{U\to E} C_T^2 = 1 \end{cases}$$

Phase Time: Superluminality for Antiparticle States

First Spinor Component Tunneling Time for Antiparticle States

$$\tau_{-}^{(2^\circ)} = -\hbar \frac{2(1-\beta^2)(\Delta k^2+\chi^2)}{E[(\Delta k^2+\chi^2)^2+4\beta^4\Delta k^2\chi^2]} + \tau_{-}^{(1^\circ)}$$

Setting: $m_0 \equiv c \equiv \hbar = 1$



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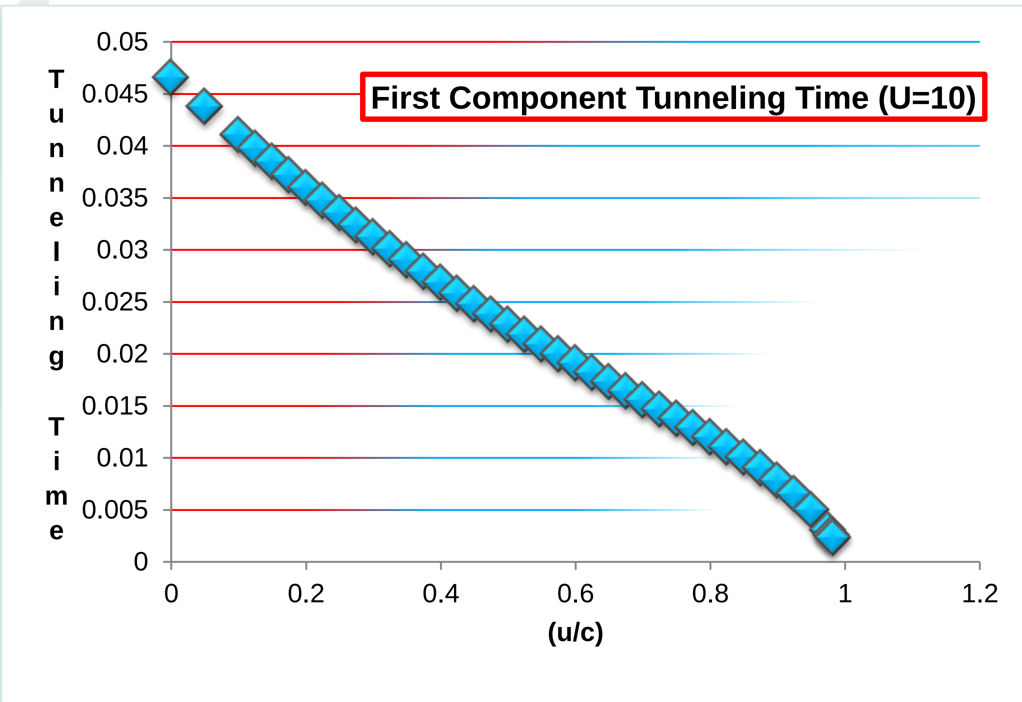
Phase Time: Superluminality for Antiparticle States

Second Spinor Component Tunneling Time for Antiparticle States

$$\tau_{-}^{(1^{\circ})} = -\frac{2m_0 \Delta k E(2\chi^2 - 1) + 2\hbar^2\chi^2\Delta k(1 - 2\Delta k^2)}{\hbar\chi E[(\Delta k^2 + \chi^2)^2 + 4\Delta k^2\chi^2]}$$

Setting: $m_0 \equiv c \equiv \hbar = 1$



It must be recall that

$$\begin{cases} \lim\limits_{U\to\infty} C_T^2 = 0 \\ \lim\limits_{U\to E} C_T^2 = 1 \end{cases}$$

Superluminal Tunneling for Particle and Antiparticle States: Is This Unphysical?

The tunneling of Particle states (first spinor component) always occurs at Superluminal velocity (*Extended Hartmann Effect*)

Negative Tunneling Time. Within the *Extended Special Relativity* **all the Casual Paradoxes concerning Tachyons may be solved. So, Superluminality due to Negative Tunneling Time is a Physical Phenomenon [3,9]. Negative Times are associated to** *Negative Velocities*. **As suggested by Recami** *"…when going from the laboratory frame O to the frame O' moving in the same direction, as the particle enter the barrier (acquiring superluminal speed) it will appear in the frame O' as an anti-object crossing the barrier in the opposite space-direction. In such a frame the anti-object yields a negative contribution to the tunneling time that, in total, could become negative".*

The tunneling of Antiparticle states (second spinor component) may occurs at Superluminal velocity (*Normal Hartmann Effect*)

- **Positive Tunneling Time. The anti-object yields a negative contribution to the tunneling time but, in total, it remains always Positive. But:**

Why does antiparticle states behave in the opposite way than particle ones?

Antiparticle tunneling occurs like that of a particle imping a barrier of height $(U + E)$, and we proved that increasing the barrier height the tunneling time increases.

Superluminal Tunneling for Particle and Antiparticle States: Spinor Distortion

The tunneling Time for the secondary spinor components of Particle/Antiparticle states is respectively delayed/in advance than the main spinor components

- **Anomalous Distortion. The difference between the tunneling times of the two spinor components $\Delta\tau$ leads to an *anomalous distortion* of the bi-spinor coming out from the barrier. This occurs also for a Gaussian non-relativistic wave packet emerging from a potential barrier. In terms of Probability Density:**

Before Tunneling $$\rho(V) = \left(1+\beta^2\right)\frac{\gamma+1}{2\gamma V}$$

After Tunneling $$\rho(V,\Delta\tau) = \left(1+{\beta_{\Delta\tau}}^2\right)\frac{\gamma+1}{2\gamma V}$$

Probability Density function *gets distorted* by the tunneling or, we can say also, *gets spread*. The *anomalous distortion* tends to disappear as the particle velocity approaches the speed of light. This *distortion* recall a cosmic superluminal *optical boom* where the source seems to split in two *objects* receding one from the other. [12]

Superluminal Tunneling as a Consequence of Energy Confinement

The Hypothesis of Evanescent Wave

The particle/antiparticle impinging the potential barrier gets *confined* **becoming an** *Evanescent Wave (characterized by an imaginary wave vector)*. **The energy gets** *localized* **into the barrier in a very short time (***Heisenberg Uncertainty Principle***):**

$$\partial t = \frac{\hbar}{(U - E)}$$

The quantum system *borrows* **from the vacuum the energy** (*like an Activation Energy*) **to surmount the barrier and repays it in a time ∂t. This time does not depend on the barrier width, tends to zero as the barrier height increases (particularly for antiparticle states).**

This suggest that the superluminal tunneling is a sort of *Intermediate state* **mathematically represented by an** *Evanescent Localized Solution (ELS)* **to the wave equation** (*any wave equation admits ELS*). **Superluminality is due to the concomitant effects of vacuum energy and energy confinement** *(the theory holds if the barrier is large enough)*. **Everything happens as if the energy was released as a** *quantum boom*.

Evanescent modes like tunneling particles are not observable inside the barrier. The quantization of an evanescent mode shows that *the locality condition is not fulfilled*. **The evanescent fields do not interact with the real ones and their commutators do** *not vanish for space-like separated points*. **Everything return to be** *physical* **once included within the Extended Theory of Special Relativity.**

Superluminal Tunneling: Critical Points in Particle Physics and Cosmology

Is this Idea Crazy enough to be Correct? **(Niels Bohr)**

Although in the last decades have been *built* **robust and** *good* **theories for Tachyons (***at least from the physico-mathematical point of view* **[10]) the skepticism and suspicion by the majority of the scientific community about the faster than light phenomena does not help to sponsor economic investments to performe sophisticated experiments! Less than 5% of the scientific literature concerns studies on superluminal phenomena (data by** *Luca Nanni***, excluding paper about string theory).**
However, according to the Galilean Method, only the *Experiment* **may confirm or not the correctness of a Theory.**
The satisfaction of finding experimental evidences confirming a given theory must have the same dignity as those that deny another theory.
Physics still does not know if massive particle may travel faster than light…and little is doing to solve this lack of knowledge.

and what's up if

- ***neutrino*** **travelling in our cosmos hits huge potential barrier? It might behaves like** *evanescent fields***, that does not interact with** *real matter***. Could this solve some unresolved problem in cosmology? To prove neutrino superluminality experiments must be performed on cosmology scale** *using* **not so high energy (muon) neutrinos (less than 17 GeV) (Recami comment on 2011 OPERA experiment) [11-12].**
- ***photons*** **(light) coming from the far universe go through huge opaque barrier with superluminal velocities…measures of galactic distances** *might be* **incorrect? [12-13]**

"Science never solves a problem without creating ten more."
George Bernard Shaw

Thanks

THANKS for your ATTENTION

and PATIENT

...

probably they have been

CRITICAL POINTS in my Talk

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