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

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Several theoretical and experimental studies in the past decades have examined phenomena involving superluminal waves and objects because of their implication in quantum and cosmological physics [1-6]. Among them, the study of the tunneling time problem is one of the topics that has most attracted the interest of quantum physicists [7-12]. Researchers have approached this issue both from the perspective of non-relativistic [13] and relativistic [14] quantum theory. In both cases the tunneling time does not depend on the barrier width (at least for large enough barriers), thus proving superluminal behaviour of the quantum object (wave or particle). However, the tunneling time problem remains a controversial one in quantum physics. A comprehensive and clear theory to explain *how long does it take a particle to tunnel through a barrier* still does not exist [15]. As is well known, *classical* quantum mechanics does not treat time as an Hermitian operator but rather as a parameter [16]. Time does not appear in the commutation relationships typical of the Hermitian operators, even if it appears in one of the forms of the Heisenberg uncertainty principle, being a physical variable conjugated to the energy. For this reason we have to give up directly knowing the tunneling time. We may bypass the obstacle by assuming that the wave packet inside the barrier is stationary, with an imaginary wave vector. We can then interpret the tunneling time as the phase variation of the evanescent localized wave that crossing the potential barrier induces. This is the definition of tunneling phase time [17-18], an asymptotical and non-local quantity.

In this paper we investigate, by the study of the phase time, the one-dimensional scattering process of a relativistic half-integer spin free particle through a rectangular barrier. When the barrier height is greater than the particle energy, for the main spinor component of particle states we prove that the tunneling process always occurs at superluminal velocity (extended Hartmann effect). This transpires regardless of the width of the barrier and the energy gap between the barrier and the relativistic particle.

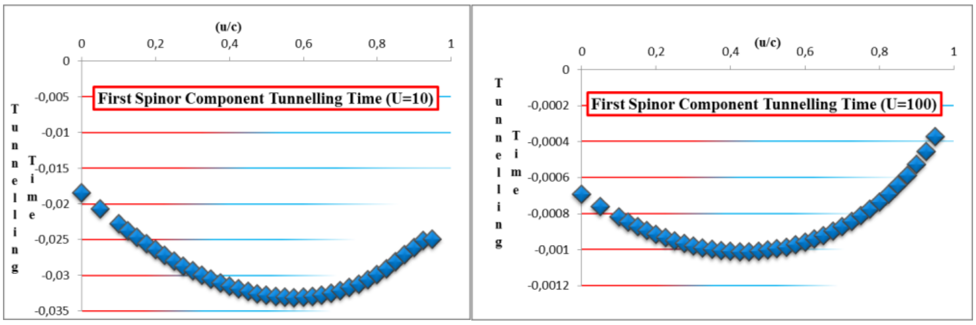

Figure 1: Tunneling time vs relativistic factor $\beta = (u/c)$ for two potential energies. All values are negative, proving that the tunneling is always superluminal. As the barrier height increases, the tunneling time tends to zero.

The main spinor component of antiparticle states, on the contrary, behaves in a different way, and the scattering through the barrier may be subluminal or superluminal, depending on the barrier width (normal Hartmann effect). Furthermore, the study shows that when the energy gap increases, the tunneling time tends to zero for both particle and antiparticle states, and the crossing velocity of the barrier diverges to infinite values.

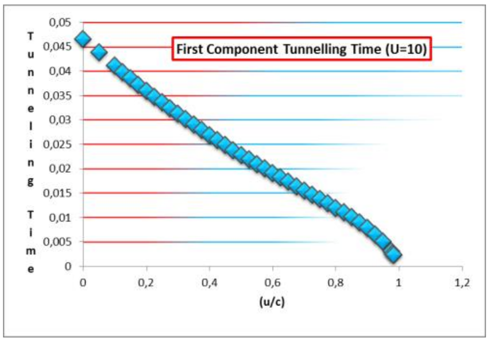

Figure 2: Phase time vs relativistic factor β for the antiparticle state for the barrier height $U = 10$. The phase time is always positive and tends to zero as the antiparticle velocity approaches the speed of light.

We also investigate the phase time of the secondary spinor component both for particle and antiparticle state, proving that a spinor *distortion* occurs when the particle velocity is quite far from its relativistic behaviour. This peculiarity disappears as the particle velocity increases, i.e., when the secondary spin component becomes more and more important (its magnitude increases as the relativistic factor $\beta = u/c$ increases).

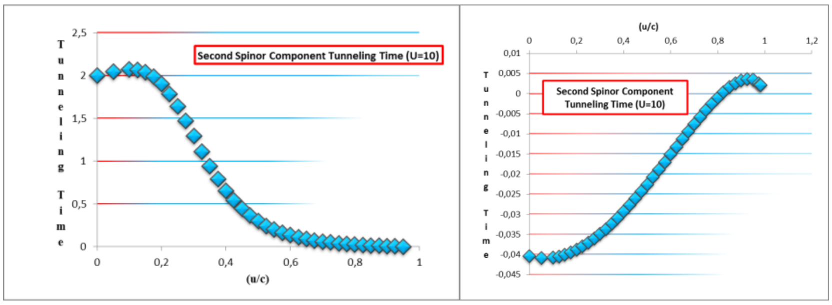

Figure 3: Phase time vs relativistic factor β for the secondary spinor component of particle and antiparticle state for the barrier height $U = 10$. The secondary spinor components of particle and antiparticle behave in opposite way.

This study's results are innovative with respect to those available in the literature. Moreover, they show that the superluminal behaviour of particles occurs in those processes involving high-energy confinement and, at least from the theoretical point of view, may affects some phenomena ranging from particle physics to cosmology.

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