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A Generalized Pilot Wave Model of Quantum Tunneling in a Dynamic Vacuum

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Abstract
We discuss the old and modern experiments of quantum tunneling, and we illustrate a new proposal based on the hypothesis of a dynamic effect of vacuum polarization on tunneling probabilities. We apply it to explain by a classical electromagnetic framework the recent experiments on dynamically assisted nuclear tunneling effects. We propose, in particular, a vacuum-dependent pilot-wave model with backreaction for particles with variable mass. We suggest a self-consistent system of coupled equations that assumes that the pilot wave is a Klein-Gordon-like scalar electromagnetic potential which determines the relative trajectory of the tunneling accelerated particle with respect to the accelerated target. We deduce a generalized time-dependent tunneling probability which depends on the hidden vacuum index and on the variable mass. We compare our relationship with the standard one based on Gamow formalism of unstable decaying states. We conceive dynamical assisted quantum tunneling as a time-dependent irreversible process whose non-Hamiltonian dynamics are controlled by hidden vacuum energy fluctuations. Endly we argue that the generalized formula of our model may pave the way to a prediction of the path-dependent tunneling time determining the real trajectory followed by the particle during tunneling.

Keywords — *variable mass, hidden vacuum index, generalized pilot-wave models, vacuum-dependent tunneling probabilities, path-dependent tunneling time.*

I. INTRODUCTION

Recent theoretical investigations and experiments on laser-assisted nuclear reactions and ionization of heavy nuclei [1]-[6] shed new light on the possible dynamical origin of the statistics of nuclear physics and suggest a realistic way to enhance lifetime decays of either fission and nuclear fusion processes. Over more since these recent proposals use classical approaches to describe nucleon dynamics, they question concretely to go beyond the assumed standard abstract border between quantum mechanics and classical physics.

In particular, we think that these studies stimulate the necessity to go beyond the standard limits posed by Heisenberg indeterminacies relations on the impossible existence of real trajectories of quantum particles.

We suggest adopting some concepts developed recently on the dynamic vacuum and vacuum friction forces [7], [8] and some ideas formalized in previous articles of the author [9]-[12]. We interpret this effective random kinematics as deterministically caused by the electromagnetic friction forces due to the radiation emitted by the accelerated tunneling projectiles, which make dependent the variable mass on the hidden vacuum index.

We think that all the models so far conceived of quantum tunneling generalizing the original Gamow theory of alpha decays [13] are unsatisfactory since they depend on unknown particles trajectories and do not consider the effect of external laser fields on the dynamic vacuum state. On the contrary, we conceive the polarized vacuum as an active time asymmetric medium which modifies the particle trajectory during tunneling and changes the height of the potential barrier, making it time-dependent.

We critique, therefore, most of the interesting recent approaches of laser-assisted nuclear reactions since they lack the backreaction effect of particles on the electromagnetic fields and the potential barrier.

These models assume that the dynamics of accelerated extended nucleons with time-dependent shape are based on the classical lagrangian formalism for punctiform particles with constant mass. These frameworks predict transition probabilities using semiclassical treatments of radiation-matter interaction depending on the unknown classical trajectories of nucleons and electrons (obtained solving the associated Newtonian equations). Over more, the most important variable describing quantum tunneling, that is, the Gamow barrier penetrability factor [14], is estimated using the old W.K.B. semiclassical approximation applied to standard quantum wavefunctions belonging to the Hilbert space [15].

We note that there are some contradictions in the standard approach used till now to describe these laser inducted quantum tunneling phenomena. On our opinion, the conflict is due to the conventional assumption to explain the irreversible microscopic processes by hamiltonian dynamics neglecting the role of dissipative forces caused by the electromagnetic emission processes of the accelerated particles [16]. Therefore we think it is inappropriate the standard use of static potential barrier, as the Coulomb one, for describing the interaction of quantum wavefunctions since it is a fast time-dependent process which makes the single nucleus potential barrier time-dependent.

We believe it is important to remark that there are just a few analytical solutions of the Schrodinger equation for a single particle in a time-dependent potential barrier, and it is over more impossible to use the Schrodinger equation to describe tunneling of composite bound states crossing time-dependent potential barrier. These mathematical obstacles make the standard approach ambiguous and incomplete since it doesn't make clear statistical predictions for every process that requires finite time duration.

We want to outline, more generally, that even in the case of a Coulomb potential of an accelerated nucleus frame, the notion of discrete stationary atomic states is not mathematically justified, and it is, therefore, unrealistic to talk of quantum jumps between these excited states [9] (a concept which inspired the Gamow theory of instantaneous quantum tunneling).

Therefore we think it is necessary to abandon this important postulate of atomic physics, that is, the Bohr postulate [17], and it is more reasonable to assume time-dependent asymmetric single atomic energy states, whose fluctuations about average values can be recovered by generalized Gamow decay factor gamma. In fact, the observed averaged finite lifetimes of unstable quantum quasi-stationary decaying states could be explained, in analogy with a model proposed by the author for describing time-dependent hydrogen energy spectra and nuclear states [9], [11], by making the standard tunneling probabilities dependent on Weber like a potential barrier, generalizing the Coulomb potential in the following way

$$(1) \quad V_{Barrier} = V_{Coulomb}\left(1 + b\frac{\vec{v}^2 n^2}{c^2}\right)$$

where b is an adimensional unknown constant, n is the vacuum index of refraction of the time asymmetric quantum vacuum, and $\vec{v}$ Is the relative velocity between the accelerated particle and the accelerated target.

We think that it could be possible to recover standard stationary predictions of the Gamow theory averaging the previous formula on the hidden velocity and the hidden vacuum index (the W.K.B approximated formula should be computed on the phase space compatible with the Bohr-Sommerfeld semiclassical condition).

This problem, in our opinion, clearly shows the inadequacy of the Copenhagen interpretation [17] to describe the irreversible dynamics of quantum processes with finite time duration and needs to be explained by new classical pilot-wave models. We think, in fact, that it is necessary to have a real spatiotemporal description of microscopic atomic and nuclear dynamics exploiting ideas analogous to those developed at the end of his life by Einstein. Unfortunately, this alternative approach was not considered by other interesting deterministic approaches as Bohmian mechanics and De Broglie pilot waves [18], even if they are completely independent of E.P.R. experiments and Bell Theorem.

We remark that at the moment, as far as we know, it still lacks a general formulation of entanglement and of Bell Theorem for accelerated quantum systems; therefore, it is viable a research program of developing a deterministic hidden variable model of nuclear reactions [11]. On the contrary, as already suggested in some previous papers of the author [9], [10], [12], since every accelerated electron or nucleon emit radiation during its tunneling, every process of this kind should be described by a classical framework with time-dependent mass, going beyond the unrealistic standard approach which it is based on adiabatic hypothesis and the quasi-stationary Hamiltonian formalism [2]. Therefore every particle during tunneling radiates in a finite time an electromagnetic wave and modify therefore the potential barrier, making it dependent on target acceleration and on the vacuum index of refraction.

We exploit an analogy of this particle-target coupled interaction with the semiclassical processes of laser-matter interaction, used, for example, to describe electron giant dipole resonance [19] in light atomic nuclei. We propose to describe this time-dependent scattering process of accelerated particles by a self-consistent model of classical electromagnetic Klein-Gordon-like potentials (aimed to describe internucleon meson forces), propagating in a polarised medium with path memory.

In fact, our view of quantum tunneling is that the interaction with the accelerated particle and nucleus is due to effective electric forces and vacuum friction forces [12], which make oscillating the potential nuclear barrier and the nucleon mass.

We propose to explain quantum tunneling as a classical wave packet dispersive propagation across the barrier of these Klein–Gordon-like electromagnetic potentials emitted by particles with variable mass; we suggest, therefore, using these potentials instead of the Coulomb one in the standard Gamow quantum tunneling probability.

We wish to outline that Standard Quantum Mechanics [17] cannot consider time durations coherently as measurable quantities since the time operator is not Hermitian; anyway, till now, the standard approach conceives four different definitions of tunneling time aimed to explain the real process that happens when a particle is crossing a potential barrier [15].

Unfortunately, these times are complex numbers, and therefore it is not obvious and well established how to use them to interpret experimental data. We believe that this inadequacy of Quantum Mechanics formalism is caused by its incompleteness, and it urges for new classical frameworks.

We will try in the next paragraph to describe quantum tunneling and tunneling time by a generalized electromagnetic pilot-wave model inspired by recent deterministic approaches developed for describing laser-induced nuclear reactions [1], [4]. We propose in the following paragraph a model which solves these ambiguities making dependent the tunneling probabilities on the hidden variable mass and vacuum index. We suggest that a non-stationary approach could be useful to describe deterministically not only atomic and nuclear quantum tunneling but atomic and molecular ionization processes.

In fact, we think it may be useful, for a better comprehension of general atomic and molecular ionization processes, to have a deterministic model which predicts the time it takes an electron or an electron beam to tunnel a barrier and may allow controlling the fluctuations of these ionization times dynamically.

Finally, we hope that our proposal will stimulate the search for deterministic time-dependent processes explaining the origin of the quantum wavefunction collapse, a search program called CSL models [20],[21]; it attracted a lot of attention recently since it seems to allow to give a new framework to unify Quantum Mechanics and General Relativity, that is, we think, the most important open problem of modern physics.

II. MODEL

We illustrate in this paragraph our proposal of a deterministic approach of quantum tunneling processes of spin-zero particles based on a reformulation of previous hidden variable models of the author concerning time-dependent atomic spectra, unstable quantum states, and nuclear reactions [9], [12].

We assume that these processes are non-stationary and have finite time durations, defined by the tunneling escape time, whose fluctuations are caused by the fluctuations of the hidden electromagnetic vacuum index.

We assume that the kinematics of the projectiles during tunneling and the time dependence of the potential target barrier are described by an electromagnetic pilot-wave model with variable propagation speed. We then deduce the electromagnetic scalar potential of this pilot wave and exploiting an analogy with the relativistic Einstein formula

$$(2)\quad \Delta m = -\frac{\Delta E_{emitted}}{c^2} = \frac{\Delta E_{absorbed}}{c^2} = \Delta\left(\frac{m}{n^2} - m\right)$$

Where n is the vacuum index defined in formula (1), and the variable mass is a consequence of the radiation emission by the accelerated particles during tunneling.

Therefore the trajectories of the tunneled particles and the target potential barrier dynamics are solutions of a system of self-consistent coupled equations, which depend on the scalar electromagnetic pilot wave and on the hidden vacuum index (which becomes imaginary or complex in the forbidden classical regime), given by the following formula [12]

$$(3)\quad n = 1 + \frac{\alpha\phi_n}{m_0 c^2}\left(\frac{\vec{v}^2}{c^2}\right)$$

Where α is a phenomenological constant dependent on the target temperature nature T, its atomic number Z, and its nucleon number A, while the vacuum index n depends on the scalar potential φ .

This formula implements our hypothesis explicitly that the vacuum index depends on the relative velocity of the tunneling particle with respect to the accelerated target, which we assume is given by the following relation

$$(4)\quad \vec{v} = \frac{h\alpha\nabla\phi_n}{2\pi n^2 c^2}$$

The scalar potential of the electromagnetic pilot wave of the interacting projectile-target system is given by a Klein-Gordon like equation with a dissipative term dependent on the unknown time-dependent potential barrier

$$(5)\quad \left(\nabla^2 - \frac{n^2}{c^2}\frac{\partial^2}{\partial t^2}\right)\phi_n - \frac{2i}{c^2\hbar^2} V\frac{\partial\phi_n}{\partial t} = \left(\frac{\Delta m^2 c^2}{\hbar^2} - \frac{V^2 n^2}{\hbar^2 c^2}\right)\phi_n$$

where the velocity-dependent potential barrier V is unknown, and its work is defined by

$$(6)\quad \Delta E_{emitted} = -\int_{t-\tau}^{t} \nabla V \cdot \vec{v}\, dt'$$

We wish to outline that notwithstanding it is usually assumed that the potential barrier is a stationary known one, for example, the Coulomb or the Yukawa potential [22], we think that it is necessary to develop a self-consistent framework; therefore, we interpret the electromagnetic radiation emitted in formula (5) as a kind of work done by a hidden symmetry breaking vacuum friction force, following a recent proposal [8], [12],

$$(7)\quad \Delta E_{emitted} = -\int_{t-\tau}^{t} e^{-\Gamma t'} m(n)\Gamma \vec{v}^2 dt'$$

where the variable Γ is a vacuum index dependent spontaneous emission rate during tunneling processes and are based on Fermi's standard golden rule [8], the variable mass *m(n)* was introduced in formula (3), and it is explicitly defined by

$$(8)\quad m(n) = m\left(\frac{1}{n^2} - 1\right).$$

Therefore the coupled system of equations (2)-(6) constitutes a self-consistent system, whose solutions can be approximated by an iterative method suggested in a previous paper of the author [11].

We insert at the first step of the power series (in the alpha constant of formula (2)) the Coulomb potential at a second member of equation (3), and we insert it in formula (2) and (4); we, therefore, can find the first approximation of the potential Barrier V and deduce from formula (5) the radiation emitted during the tunneling process and the gamma lifetime of the process of formula (6).

We propose to describe the space time-dependent tunneling probability by the following formula

(9) $p_{tunnell}(t, t-\tau) = \gamma(z) \int_{t-\tau}^{t} e^{-\Gamma t'} dt'$

Where the hidden tunneling time was introduced in relations (5) and (6).

We think that our approach could be adapted to recover the approximated stationary W.K.B. tunneling probabilities dynamically, inserting in the standard formulas the hidden scalar potential V of equation (4) and the variable mass of equation (3) in the following relation

(10)

$$p_{tunnell} \propto exp\left[-\frac{2}{\hbar}\int_{P(n)}^{P(n')} \sqrt{2m(n)(E-V)}\vec{v}dt'\right]$$

with P*(n')* and P*(n)*, respectively, the initial and final positions of the tunneling stopping points (defined by the condition that the gradient of the mass variation is zero),

(11) $\nabla m(P) = 0$

And where the integral is along the trajectory determined by the velocity of formula (3).

We think it could be interesting to find the asymptotic limit of this formula when the time goes to infinity and to compare the non-stationary tunneling probability with those recently proposed in laser-assisted nuclear reactions [2], substituting the variable mass in the integrand of formula (7) with laser-induced effective mass variation

(12) $\lim_{t\to\infty} \Delta\, m(n) = \frac{\omega\hbar}{c^2}$

This formula can be used to compute enhanced decay times, inserting the external laser photon energy and finding the final vacuum index when there is no more interaction with the target at the end of the tunnel. This framework conceives the processes as non-adiabatic [1], but differently from this proposal, it doesn't assume that the potential barrier effect is negligible.

We want to remark that our tentative classical pilot-wave model suggests developing a new formalism by which it is possible to deduce the tunneling probability dynamically and maybe the dynamic origin of Born probability interpretation of the quantum wavefunction.

We speculate that it would be possible to pave the way to this generalization of our model, making dependent the tunneling probability on the divergence of a hidden vacuum breaking density currents J in the following way

(13) $\frac{dp_{tunnell}}{dt} \propto \int_1^n div\overrightarrow{J(n')}\,\rho(n')dn'$

Where the integral is computed on the ensemble average of target vacuum indexes space. It is assumed to give a realistic interpretation to the scalar potential introducing in equation (5) the standard electrodynamic relation for the hidden vacuum polarization current

(14) $\vec{J}(n) = \sigma(n)\overrightarrow{E(n)}$

with $\sigma(n)$ the vacuum electric conductivity and $\vec{E}$ the electric vector field of the coupled system projectile - barrier, whose force is given by an analogous statistical ensemble average

(15) $Ze\overrightarrow{E(n)} = -\alpha \int_1^n \nabla\varphi(n')\,\rho(n')dn'.$

We think that this classical electrodynamic approach may allow us to compute the tunneling time, interpreting its fluctuations as caused by the vacuum index fluctuations.

We wish to remark that some strange phenomena in atomic and nuclear processes with non-exponential decay tunneling time [23] could be explained by introducing effective electromagnetic scalar potentials and hidden vacuum electric current densities defined by the relations (14) and (15).

We want to outline the growing importance of present technological applications on semiconductors and superconductors to have a dynamic deterministic model of macroscopic wavefunctions quantum tunneling [24].

In fact, we think that this task may be implemented, we think, once that is accomplished, a realistic space-time description of the real trajectories of quantum particles and giving a physical interpretation of the Bose-Einstein atomic condensate wave functions. We remark that our tentative model based on scalar potentials could be generalized to describe spinning particles making the vacuum index dependent on the electromagnetic vector potential of the target.

We hope that our proposal and its possible generalizations will allow us to overcome the ambiguities and the contradictions produced by the standard approach. In fact, we think that modern experiments on dynamically assisted quantum tunneling urge us to conceive new classical pilot wave-like approaches which may give realistic meaning to microscopic and macroscopic quantum wavefunctions.

Endly we speculate, that our proposal may be important for the future aim of dynamic control of radioactive nuclear decays and future effective exploitation of atomic and nuclear energies.

III. CONCLUSIONS

We study in this work the old problem of quantum tunneling and the growing modern development of classical models aimed to describe the dynamics of recently discovered laser-assisted nuclear tunneling processes.

We propose to explain the hidden microscopic kinematics and dynamics of these nonstationary irreversible processes by a tentative self-consistent pilot-wave model with vacuum-induced backreaction.

We modify the standard tunneling probabilities formulas making them dependent on this variable vacuum index of refraction and on the relative velocity between the accelerated particle and the accelerated target.

We, therefore, explain the dynamics of laser-assisted quantum tunneling as caused by classical electromagnetic phenomena of radiation emission from accelerated systems in a dynamic vacuum whose vacuum index of refraction makes particle mass variable across the non-stationary potential barrier.

We interpreted the supposed enhancement of dynamically assisted nuclear reactions to be caused by vacuum energy fluctuations which govern the projectile trajectory by hidden vacuum friction forces.

We propose an iterative approximate method to solve our equations for the pilot wave electromagnetic scalar potentials and particle velocities, and we explain how to recover the scattered standard quantum wavefunctions.

We modify the standard W.K.B. approximated tunneling probability, and we propose a new one dependent on the dynamic vacuum index, whose ensemble average could recover the known one.

We extend our pilot-wave self-consistent model introducing a hidden vacuum density electric current, which, we suggest, could explain the dynamic origin of Born probabilistic interpretation of quantum wavefunctions and justify its application to tunneling probabilities of unstable decaying states.

We hope that our work will stimulate future researches on generalized pilot-wave electromagnetic models, which could allow, we think, to give a realistic interpretation to the atomic and molecular quantum wavefunctions.

This novel reformulation of quantum wave functions as real electromagnetic potentials may in the future pave the way to quantitative deterministic predictions of atomic and molecular ionization times.

We leave for future work the generalization of our vacuum-dependent pilot-wave model to spinning particles exploring the role of the atomic and molecular electromagnetic vectorial potentials to control semiconductors bandgaps and resonant tunnel diodes dynamically.

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