Effective Field Dynamics and Quantum Emergence from Intrinsic Oscillations in a Bounded Vacuum

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Date: 11-April-2026

We extend the bounded-vacuum framework introduced in Ref. [1] by incorporating the intrinsic dynamical properties of localized vacuum configurations and deriving a unified effective field equation for the vacuum potential $\Phi(x, t)$. In this approach, matter is identified as a localized vacuum loading corresponding to a deficit of the vacuum potential. We show that stable vacuum loading configurations have their own intrinsic degrees of freedom associated with vibrations of definite frequency ω_0; small deviations from the equilibrium satisfy the Klein–Gordon-type equation, so that the dispersion relation gives the known energy-momentum dependence $E^2 = p^2c^2 + m^2c^4$, where mass originates due to the condition $\hbar\omega_0 = mc^2$. The field equation under discussion includes not only the wave propagation, but the effect of gravity and the restoring force which represents a sort of the vacuum capacity limitation; in such a way we get the unified treatment of the problem of both massive and massless particles. Within the nonrelativistic limit, the theory turns out to be nothing else but the Schrödinger equation with the effective potential associated with fluctuations of the vacuum potential.

I. Introduction

As reported in Ref. [1], we introduced the notion of a bounded vacuum model, in which both gravitational interaction and wave dynamics can be viewed as arising from a scalar potential field, $\Phi(\mathbf{x}, t)$. In such a scenario, the vacuum can be understood as having a bounded capacity, normalized by $\Phi_0 \equiv c^2$, as its maximum energy per unit mass, corresponding to the vacuum's capacity to host the matter content of the universe. Deviations from this equilibrium state lead to a vacuum loading condition, allowing one to understand mass as a deficit integral of the vacuum field. Herein, gravity can be seen as a static relaxation process of the vacuum field, while wave-like phenomena emerge as the propagation of disturbances in the vacuum field, similar to relativistic fields [2].

In the present study, we extend the previous model [1] by considering the dynamical properties of vacuum loading and presenting a unified effective equation for vacuum wave dynamics and internal vacuum response. While Ref. [1] presented how gravitational interactions and relativistic waves can be modeled within our bounded vacuum theory, it did not provide any information regarding the dynamical properties of vacuum loading and their stability.

Our main finding is that vacuum loading possesses inherent oscillatory properties, which can be defined in terms of a characteristic frequency ω_0.. We prove that small perturbations around a stable vacuum loading exhibit oscillatory motion according to a Klein-Gordon type equation, leading directly to the relativistic energy-momentum relation.

$$E^2 = p^2c^2 + m^2c^4.$$

In this framework, the inertial mass is related to the natural oscillation frequency of the particle according to the expression $\hbar\omega_0 = mc^2$, thus providing a dynamic explanation for mass in terms of the vacuum theory. Expanding on the above result, we can formulate an effective field equation for the vacuum potential including three crucial factors: propagation of waves based on the relativistic d'Alembert operator, gravitational sourcing via the vacuum loading density, and a restoring force term based on the oscillation nature of the localized configurations. Such an equation serves as a generalization of the field equation and provides an unification of both massless and massive excitations of the vacuum. Moreover, one can show that in the nonrelativistic limit, our theory reduces to the Schrödinger equation where the effective potential is defined as the deviation from the asymptotic potential of the vacuum. Finally, we argue that the interpretation of probability in quantum mechanics emerges directly from the local energy density of vacuum excitations providing a physical rationale for the Born's Rule [3], [4], [5].

The model outlined in this paper combines a number of important aspects of basic physics into one description system: gravity as a result of vacuum relaxation, special relativity from the perspective of vacuum propagation, and quantum mechanics as modulation of vacuum oscillations. Despite being limited to a weak-field scenario using a scalar field formulation, the described analysis represents a consistent step towards a unified field theory from the point of view of bounded vacuums.

II. Vacuum Potential Field and Normalization

The bounded-vacuum framework introduced in Ref. [1] is formulated in terms of a scalar potential field $\Phi(\mathbf{x}, t)$, interpreted as the **energy per unit mass** associated with the local state of the vacuum. The detailed construction and motivation of this field have been presented in Ref. [1]. We summarize only the essential elements required for the present development.

A central feature of the framework is that the vacuum possesses a **finite capacity**, such that the potential is bounded according to

$$0 \leq \Phi(\mathbf{x}, t) \leq c^2, \qquad (2.1)$$

where the reference value

$$\Phi_0 \equiv c^2 \qquad (2.2)$$

This corresponds to the asymptotic, unloaded vacuum state. The normalization condition guarantees compatibility with the relativistic expression for energy-mass equivalence, where the energy of a mass m configuration within the vacuum is

$$E = m\Phi, \qquad (2.3)$$

which reduces to the rest-energy relation $E = mc^2$ in the reference state.

For later convenience, we define the deviation of the vacuum potential from its reference value as

$$\varphi(\mathbf{x}, t) \equiv \Phi(\mathbf{x}, t) - c^2, \qquad (2.4)$$

In this description, the inequality $\varphi \leq 0$ refers to a vacuum deficit in the vicinity of that region. The matter is characterized by the partial depletion of vacuum energy in localized regions, and the value of φ represents the loading level.

The dynamics of the vacuum are determined by its capability to carry disturbances, as described in Ref. [1]. The speed of disturbance propagation is established by the tension of the vacuum T relative to the loading density μ,

$$v^2 = \frac{T}{\mu}. \qquad (2.5)$$

In the case of the homogeneous and weakly perturbed system, the bound nature of the vacuum leads to the requirement:

$$\frac{T}{\mu} = c^2, \qquad (2.6)$$

ensures propagation of disturbances at the invariant speed c. This relationship is the basis for the dynamics of relativistic waves under conditions of the bounded vacuum.

For the static case, the vacuum potential determines the strength of the forces acting on the test configuration. According to Eq. (2.3), the force exerted on the test particle with mass m_t is

$$\mathbf{F} = -\nabla E = -m_t \nabla \Phi. \qquad (2.7)$$

which corresponds to the definition of the gravitational force used in classical theory [6]. The gradient of the vacuum potential acquires the meaning of a gravitational field in accordance with the approach suggested in Ref. [1].

It is important to emphasize that there exist two aspects to the potential function Φ: it controls both the state of energy of the vacuum and the dynamics of the disturbances. This duality makes it possible to describe in one theoretical framework the gravitational interactions and processes of wave propagation. In particular, the normalization of the potential to $\Phi_0 = c^2$ ensures the unified energy and velocity reference. Further development of the model, which we will consider in the next sections, includes postulating mass as a vacuum loading parameter, studying the internal dynamics of the localized system, and deriving the effective field equations combining propagation, gravitation, and quantum effects.

III. Mass as Vacuum Loading and Static Relaxation

In the bounded-vacuum framework approach, matter is not treated as a separately introduced element but is considered equivalent to vacuum loading in localized form, which represents a deviation of the vacuum potential from its reference level. The calculations leading to the solution of the corresponding static field problem have been described in Ref. [1]. Here, we will simply list the relevant outcomes of this procedure necessary for the subsequent considerations.

Using the deviation field discussed in Section II,

$$\varphi(\mathbf{x}, t) \equiv \Phi(\mathbf{x}, t) - c^2, \qquad (3.1)$$

the localized solutions for which $\varphi < 0$ represent states where the vacuum capability has been partly exhausted. For the weak field approximation, such states can be easily represented using an effective loading density $\rho_{\text{load}}(\mathbf{x})$, in such a manner that the mass m is the result of the integral,

$$m = \int \rho_{\text{load}}(\mathbf{x})\, d^3x. \qquad (3.2)$$

In this approach, the notion of mass takes on a practical sense as an integral representation of vacuum depletion, intrinsic property of an independent particle. In this sense, mass emerges as a collective property of the vacuum configuration. In regions where the loading density vanishes, the vacuum potential satisfies the homogeneous field equation

$$\nabla^2\Phi = 0, \qquad (3.3)$$

Here, the solution obeys boundary conditions due to the application of a localized load. If we have a spherical symmetric system with a total load m, the asymptotic solution is expressed as [1]:

$$\Phi(r) = c^2 - \frac{Gm}{r}, \qquad (3.4)$$

which uses the boundary condition $\Phi \to c^2$ as $r \to \infty$.

The gravitational force can be obtained directly based on the variation of the vacuum potential. With the use of the energy equation $E = m_t\Phi$ for a test mass m_t, the force is found as

$$\mathbf{F} = -\nabla E = -m_t\nabla\Phi, \qquad (3.5)$$

and upon using Eq. (3.4), we reproduce the Newtonian force law of gravitation. Here, gravitation can be seen as the effect of the spatial relaxation of the vacuum potential rather than as a fundamental interaction.

As the vacuum is bounded, a characteristic size is expected for strong loading. From the boundary condition $\Phi \geq 0$, the asymptotic form (3.4) implies a limiting radius

$$r_c = \frac{Gm}{c^2}, \qquad (3.6)$$

at which the vacuum potential would approach zero under complete local depletion. This scale represents a **collapse radius** beyond which the linear approximation underlying Eq. (3.4) is no longer valid.

With regard to the concept of mass in terms of vacuum loading, we have achieved a common ground for both the inertial and gravitational characteristics of matter. Since both the energy of a configuration and the forces it experiences are determined by the same potential field Φ, there is no distinction between inertial and gravitational mass at the fundamental level. This equivalence arises naturally from the vacuum-based description and does not require additional assumptions.

The above-presented facts define the static aspects of the bounded-vacuum theory: mass becomes a vacuum load, and gravity appears due to vacuum relaxation. The dynamic side of the problem is presented in the next section, where we prove that any localized vacuum configuration has inherent oscillation characteristics, leading to relativistic wave equations.

IV. Intrinsic Oscillatory Dynamics from Vacuum Energy Functional

In Sec. III, localized vacuum loading was identified with stable configurations of the vacuum potential $\Phi(\mathbf{x}, t)$, corresponding to regions of reduced vacuum capacity. While the static properties of such configurations determine gravitational interaction, their dynamical behavior requires an analysis of stability under perturbations. We now show that intrinsic oscillatory dynamics arises naturally from the structure of the vacuum energy functional, without invoking any prior assumptions about relativistic energy–momentum relations.

We consider a localized equilibrium configuration $\Phi_*(\mathbf{x})$, representing a stationary vacuum-loading distribution. Small perturbations about this configuration are introduced as

$$\Phi(\mathbf{x}, t) = \Phi_*(\mathbf{x}) + \eta(\mathbf{x}, t), \qquad (4.1)$$

where $|\eta| \ll c^2$. The dynamics of the vacuum field is assumed to follow from an effective action of the form

$$S = \int d^4x \left[\frac{1}{2c^2}(\partial_t\Phi)^2 - \frac{1}{2}(\nabla\Phi)^2 - V(\Phi)\right], \qquad (4.2)$$

where $V(\Phi)$ is an effective vacuum energy density reflecting the bounded nature of the vacuum. Its existence follows from the assumption that the vacuum admits stable localized configurations [7].

Expanding the potential around the equilibrium configuration Φ_*, we write

$$V(\Phi) = V(\Phi_*) + \frac{dV}{d\Phi}\Big|_{\Phi_*}\eta + \frac{1}{2}\frac{d^2V}{d\Phi^2}\Big|_{\Phi_*}\eta^2 + \cdots . \qquad (4.3)$$

Since Φ_* corresponds to a stationary configuration, it satisfies

$$\frac{dV}{d\Phi}\Big|_{\Phi_*} = 0, \qquad (4.4)$$

so that the linear term vanishes. Retaining terms up to quadratic order, we define

$$\omega_0^2 \equiv c^2 \frac{d^2V}{d\Phi^2} |_{\Phi_*}, \qquad (4.5)$$

which characterizes the local curvature of the vacuum energy functional and therefore the stability of the configuration.

Substituting Eq. (4.1) into the action and retaining terms up to second order in η, we obtain the effective Lagrangian density for fluctuations,

$$\mathcal{L}_{\text{eff}} = \frac{1}{2c^2}(\partial_t \eta)^2 - \frac{1}{2}(\nabla \eta)^2 - \frac{1}{2}\frac{\omega_0^2}{c^2}\eta^2. \qquad (4.6)$$

The Euler–Lagrange equation for η,

$$\frac{\partial \mathcal{L}}{\partial \eta} - \partial_t \left(\frac{\partial \mathcal{L}}{\partial(\partial_t \eta)} \right) - \nabla \cdot \left(\frac{\partial \mathcal{L}}{\partial(\nabla \eta)} \right) = 0, \qquad (4.7)$$

yields

$$\boxed{\partial_t^2 \eta - c^2 \nabla^2 \eta + \omega_0^2 \eta = 0.} \qquad (4.8)$$

Equation (4.8) describes the intrinsic oscillatory dynamics of localized vacuum configurations. The term proportional to ω_0^2 arises directly from the curvature of the vacuum energy functional and represents a restoring force that stabilizes the configuration. This result is obtained purely from the internal structure of the vacuum and does not rely on any external assumptions regarding relativistic kinematics.

To analyze the propagation of these fluctuations, we consider plane-wave solutions of the form

$$\eta(\mathbf{x}, t) = A e^{i(\mathbf{k}\cdot\mathbf{x} - \omega t)}, \qquad (4.9)$$

which lead to the dispersion relation

$$\boxed{\omega^2 = c^2 k^2 + \omega_0^2.} \qquad (4.10)$$

This relation shows that localized vacuum excitations possess a nonzero frequency even in the long-wavelength limit, reflecting their intrinsic oscillatory nature. The presence of the term ω_0^2

distinguishes these excitations from massless propagating disturbances and encodes the effect of vacuum boundedness.

The physical interpretation of Eq. (4.8) is that a localized vacuum loading behaves as a self-consistent oscillatory excitation of the vacuum. The propagation term $c^2\nabla^2\eta$ governs the spread of disturbances, while the restoring term ensures localization and stability. The coexistence of these features provides a natural dynamical basis for wave–particle duality within the bounded-vacuum framework.

It is important to emphasize that the oscillatory behavior derived here originates entirely from the structure of the vacuum energy functional. In particular, no assumption of the relativistic energy–momentum relation has been made at this stage. As we show in Sec. VI, the relativistic dispersion relation and the associated identification of inertial mass emerge as consequences of the vacuum dynamics described by Eq. (4.8).

The results of this section therefore establish the intrinsic dynamical structure of localized vacuum configurations. In the following section, this behavior is incorporated into the full vacuum field equation, leading to a unified description of propagation, gravitational sourcing, and intrinsic oscillations.

V. Effective Field Equation with Emergent Restoring Dynamics

The intrinsic oscillatory dynamics derived in Sec. IV establishes that localized vacuum configurations behave as stable excitations governed by a Klein–Gordon-type equation. We now incorporate this intrinsic restoring behavior into the full vacuum potential description and construct an effective field equation that unifies propagation, gravitational sourcing, and local oscillatory response.

In the absence of vacuum loading, the bounded vacuum supports propagating disturbances with invariant speed c, consistent with relativistic field dynamics [7]. The vacuum potential therefore satisfies the homogeneous wave equation

$$\frac{1}{c^2}\partial_t^2\Phi - \nabla^2\Phi = 0. \qquad (5.1)$$

Within the present framework, matter is identified as a localized vacuum loading described by a density $\rho_{\text{load}}(\mathbf{x},t)$. The field equation generalizes to

$$\frac{1}{c^2}\partial_t^2\Phi - \nabla^2\Phi = S(\mathbf{x},t), \qquad (5.2)$$

where the source term S must be proportional to ρ_{load},

$$S = \alpha\,\rho_{\text{load}}. \qquad (5.3)$$

The coefficient α is determined from the static limit. For time-independent configurations, Eq. (5.2) reduces to

$$\nabla^2\Phi = -\alpha\,\rho_{\text{load}}. \qquad (5.4)$$

Requiring consistency with the asymptotic gravitational potential

$$\Phi(r) = c^2 - \frac{Gm}{r}, \qquad (5.5)$$

and using the standard identity $\nabla^2(1/r) = -4\pi\delta^{(3)}(\mathbf{x})$ from classical field theory [2], we obtain

$$\nabla^2\Phi = 4\pi G\,\rho_{\text{load}}, \qquad (5.6)$$

which fixes

$$\alpha = -4\pi G. \qquad (5.7)$$

Substituting this result into Eq. (5.2), we obtain the sourced vacuum field equation

$$\boxed{\frac{1}{c^2}\partial_t^2\Phi - \nabla^2\Phi = \frac{4\pi G}{c^2}\rho_{\text{load}}.} \qquad (5.8)$$

Equation (5.8) describes both the propagation of vacuum disturbances and their sourcing by localized vacuum loading. The representation of ρ_{load} as a localized distribution should be understood as an effective coarse-grained description of a finite vacuum-deficit region, rather than a fundamental point source.

We now incorporate the intrinsic restoring dynamics derived in Sec. IV. Writing the field relative to the vacuum reference state,

$$\Phi(\mathbf{x},t) = c^2 + \phi(\mathbf{x},t), \qquad (5.9)$$

the fluctuation ϕ obeys, to leading order,

$$\partial_t^2\phi - c^2\nabla^2\phi + \omega_0^2\phi = 0. \qquad (5.10)$$

Combining this intrinsic oscillatory behavior with the sourced equation (5.8), we obtain the unified effective field equation

$$\boxed{\frac{1}{c^2}\partial_t^2\Phi - \nabla^2\Phi + \frac{\omega_0^2}{c^2}(\Phi - c^2) = \frac{4\pi G}{c^2}\rho_{\text{load}}.} \qquad (5.11)$$

Equation (5.11) provides a unified description of bounded-vacuum dynamics. The first two terms represent wave propagation, the source term describes gravitational interaction arising from vacuum loading, and the additional term proportional to $(\Phi - c^2)$ encodes the intrinsic restoring tendency of the vacuum toward its equilibrium state. This restoring term originates from the curvature of the vacuum energy functional, as established in Sec. IV.

The structure of Eq. (5.11) naturally connects two limiting regimes. In the absence of intrinsic oscillations ($\omega_0 \to 0$), the equation reduces to the sourced wave equation (5.8), describing freely propagating vacuum disturbances. Conversely, in regions where the loading vanishes ($\rho_{\text{load}} = 0$), it reduces to the Klein–Gordon-type equation governing localized vacuum excitations.

The effective field equation may also be derived from an action principle. Consider the Lagrangian density

$$\mathcal{L} = \frac{1}{2c^2}(\partial_t \Phi)^2 - \frac{1}{2}(\nabla \Phi)^2 - \frac{1}{2}\frac{\omega_0^2}{c^2}(\Phi - c^2)^2 - \frac{4\pi G}{c^2}\rho_{\text{load}}\,\Phi, \qquad (5.12)$$

whose variation with respect to Φ yields Eq. (5.11), consistent with standard field-theoretic formulations [7].

We emphasize that Eq. (5.11) is valid in the weak-field regime and for small deviations from equilibrium. In regions of strong vacuum loading, nonlinear corrections to the effective potential and the detailed structure of ρ_{load} may become important. Nevertheless, Eq. (5.11) captures the leading-order behavior and provides a unified framework for describing propagation, gravitation, and intrinsic oscillatory dynamics.

VI. Physical Interpretation of the Dispersion Relation and Emergent Relativistic Dynamics

The intrinsic oscillatory dynamics derived in Sec. IV leads to the dispersion relation

$$\omega^2 = c^2 k^2 + \omega_0^2, \qquad (6.1)$$

which characterizes the propagation of localized vacuum excitations. We now examine the physical content of this relation and show how relativistic dynamics emerges from it.

A key feature of Eq. (6.1) is that the frequency remains nonzero in the long-wavelength limit. For

$$k = 0, \qquad (6.2)$$

one obtains

$$\omega = \omega_0. \qquad (6.3)$$

This shows that a localized vacuum excitation possesses an intrinsic rest oscillation even in the absence of spatial propagation. The corresponding rest energy is therefore

$$E_0 = \hbar\omega_0. \qquad (6.4)$$

Within the bounded-vacuum framework, the vacuum potential is interpreted as energy per unit mass, with the asymptotic reference value

$$\Phi_0 = c^2. \qquad (6.5)$$

A localized configuration of inertial mass m therefore has rest energy

$$E_0 = m\Phi_0 = mc^2. \qquad (6.6)$$

Equating the two expressions for the rest energy gives

$$\boxed{\hbar\omega_0 = mc^2.} \qquad (6.7)$$

Thus, the intrinsic oscillation frequency of a localized vacuum configuration is the dynamical expression of its rest energy. The mass parameter is not introduced independently, but arises from the internal oscillatory structure determined by the curvature of the vacuum energy functional.

To connect the dispersion relation with observable quantities, we use the standard wave-particle correspondences [3] [5],[8].

$$E = \hbar\omega, \mathbf{p} = \hbar\mathbf{k}. \qquad (6.8)$$

Substituting Eq. (6.8) into Eq. (6.1), we obtain

$$E^2 = p^2c^2 + (\hbar\omega_0)^2. \qquad (6.9)$$

Using Eq. (6.7), this becomes

$$\boxed{E^2 = p^2c^2 + m^2c^4.} \qquad (6.10)$$

Equation (6.10) is therefore not assumed a priori, but follows from the vacuum dispersion relation together with the identification of $\hbar\omega_0$ as the rest energy of the localized vacuum excitation. The term p^2c^2 represents the contribution from propagation, while the term m^2c^4 originates from the intrinsic rest oscillation of the vacuum configuration.

The propagation velocity is determined by the group velocity,

$$v = \frac{\partial \omega}{\partial k} = \frac{c^2 k}{\omega}, \qquad (6.11)$$

which, using Eq. (6.8), may be written as

$$v = \frac{pc^2}{E}. \qquad (6.12)$$

Combining this with Eq. (6.10), one obtains

$$E = \frac{mc^2}{\sqrt{1 - v^2/c^2}}, \qquad (6.13)$$

which is the standard relativistic energy–velocity relation.

The physical interpretation is clear. A localized vacuum excitation carries a nonzero rest energy because the bounded vacuum supports intrinsic oscillations about a stable loaded configuration. Spatial propagation adds a momentum-dependent contribution, and the combination of these two effects yields the full relativistic dynamics. In this way, the relativistic energy–momentum relation emerges as a consequence of the dispersion properties of the vacuum field.

VII. Nonrelativistic Limit and Emergent Quantum Dynamics

The dispersion relation derived in Sec. IV,

$$\omega^2 = c^2 k^2 + \omega_0^2, \qquad (7.1)$$

provides a unified description of both propagation and intrinsic oscillatory behavior of localized vacuum excitations. As shown in Sec. VI, the parameter ω_0 is directly related to the rest energy of the configuration through $E_0 = \hbar\omega_0 = mc^2$. We now examine the low-energy limit of this relation and show that nonrelativistic quantum dynamics emerges as an effective description of slowly varying vacuum excitations.

Rewriting Eq. (7.1), we obtain

$$\omega = \omega_0 \sqrt{1 + \frac{c^2 k^2}{\omega_0^2}}. \qquad (7.2)$$

In the nonrelativistic regime, where

$$ck \ll \omega_0, \qquad (7.3)$$

this expression can be expanded as

$$\omega \approx \omega_0 + \frac{c^2 k^2}{2\omega_0}. \qquad (7.4)$$

Using the standard wave–particle correspondences introduced by Louis de Broglie and developed in quantum mechanics [3], [5], [8],

$$E = \hbar\omega, \mathbf{p} = \hbar\mathbf{k}, \qquad (7.5)$$

and substituting $\hbar\omega_0 = mc^2$, we obtain

$$E \approx mc^2 + \frac{p^2}{2m}, \qquad (7.6)$$

which separates the total energy into a dominant rest-energy contribution and a smaller kinetic term. This is the standard nonrelativistic energy expansion [3], [5].

To extract the corresponding wave dynamics, we express the field as

$$\phi(\mathbf{x}, t) = \psi(\mathbf{x}, t)\, e^{-i\omega_0 t}, \qquad (7.7)$$

where the rapidly oscillating factor represents the intrinsic rest oscillation of the vacuum configuration, and $\psi(\mathbf{x}, t)$ is a slowly varying envelope. This separation of scales is standard in the derivation of nonrelativistic quantum dynamics from relativistic wave equations [3], [5].

Substituting Eq. (7.7) into the Klein–Gordon-type equation obtained in Sec. IV,

$$\partial_t^2\phi - c^2\nabla^2\phi + \omega_0^2\phi = 0, \qquad (7.8)$$

and retaining leading-order terms in the slow-variation approximation, we obtain

$$-2i\omega_0\, \partial_t\psi - c^2\nabla^2\psi = 0. \qquad (7.9)$$

Multiplying by $\hbar/(2\omega_0)$and using $\hbar\omega_0 = mc^2$, this reduces to

$$\boxed{i\hbar\, \partial_t\psi = -\frac{\hbar^2}{2m}\nabla^2\psi,} \qquad (7.10)$$

which is the free-particle Schrödinger equation originally formulated by Erwin Schrödinger [5].

In the presence of a slowly varying vacuum potential,

$$\Phi(\mathbf{x}, t) = c^2 + \varphi(\mathbf{x}, t), \qquad (7.11)$$

the energy of a localized configuration becomes $E = m\Phi = mc^2 + m\varphi$, leading to the generalized equation

$$\boxed{i\hbar\, \partial_t \psi = \left(-\frac{\hbar^2}{2m}\nabla^2 + m\,\varphi(\mathbf{x}, t)\right)\psi,} \qquad (7.12)$$

which is the Schrödinger equation with an external potential [3], [5].

The structure of Eq. (7.7) provides a clear physical interpretation. The factor $e^{-i\omega_0 t}$ represents the intrinsic oscillation associated with the rest energy of the vacuum configuration, while the envelope $\psi(\mathbf{x}, t)$ describes its slowly varying dynamical behavior. This separation of scales reflects the underlying dispersion relation and is responsible for the emergence of nonrelativistic quantum dynamics.

It is important to emphasize that the Schrödinger equation is not introduced as an independent postulate. Rather, it arises as the low-energy limit of the vacuum field dynamics governed by Eq. (7.1), consistent with the standard formulation of quantum mechanics [3], [5]. In this way, nonrelativistic quantum behavior appears as an emergent feature of the bounded-vacuum framework.

VIII. Discussion and Conclusions

In this work, we have developed an effective field-theoretic formulation of the bounded-vacuum framework, in which both relativistic and nonrelativistic dynamics emerge from the intrinsic structure of the vacuum. The central result of the analysis is that localized vacuum-loading configurations possess intrinsic oscillatory degrees of freedom determined by the curvature of the vacuum energy functional. Linearization about such configurations leads to a Klein–Gordon-type equation whose dispersion relation,

$$\omega^2 = c^2 k^2 + \omega_0^2,$$

provides a unified description of propagation and localization.

A key feature of the present formulation is that the dispersion relation is derived directly from the vacuum energy functional, without invoking the relativistic energy–momentum relation as an initial assumption. Instead, relativistic dynamics emerges from the identification of the intrinsic rest oscillation energy with $E_0 = \hbar\omega_0$, which, combined with the vacuum normalization $\Phi_0 = c^2$, yields $E_0 = mc^2$. The full energy–momentum relation then follows as a consequence of the dispersion relation, consistent with the standard formulation of relativistic mechanics [3], [5].

In the low-energy limit, the same dispersion relation reduces to the nonrelativistic energy expansion, and the Klein–Gordon-type dynamics leads to the Schrödinger equation through a separation of fast and slow time scales. This procedure, which parallels standard derivations in quantum mechanics [3], [5], shows that nonrelativistic quantum behavior arises as an effective description of slowly varying vacuum excitations. In this way, both relativistic and quantum dynamics are traced back to a common underlying structure.

Another unification brought about by the derived effective field equation can be realized with respect to propagation, gravitational sourcing, and the internal dynamics of restoring force fields. According to this model, the source of matter will be the vacuum load and gravity will arise from the spatial relaxation of the vacuum load potential. The loading density ρ_{load} should therefore be viewed as a coarse graining of a localized vacuum deficit structure rather than an external matter loading, consistent with field theory approaches [2].

A further issue arises with respect to the source term. In the current formulation of the theory, a sourced field equation is utilized. However, since the concept of mass is considered to be equivalent to the vacuum deficit structure, at a more fundamental level of description, one would expect the theory to be described by a nonlinear field equation wherein the effective source depends on the field itself. In the weak-deficit regime considered here, such a formulation reduces to the linear equation (5.11), ensuring consistency with the asymptotic $1/r$ behavior.

The nonrelativistic regime provides an interpretation of the wavefunction amplitude naturally due to the inherent structure. Using the effective Lagrangian given in Section IV, the energy density of the fluctuation field can be written schematically as follows:

$$\mathcal{E} \sim (\partial_t \phi)^2 + c^2 (\nabla \phi)^2 + \omega_0^2 \phi^2.$$

Using the expansion $\phi(\mathbf{x}, t) = \psi(\mathbf{x}, t) e^{-i\omega_0 t}$ and taking an average over the fast oscillations, the leading term is

$$\mathcal{E} \propto | \psi(\mathbf{x}, t) |^2.$$

This leads to the conclusion that the square of the effective wavefunction amplitude is proportional to the energy density in the vicinity, giving rise to a physical interpretation of $| \psi |^2$ as the probability density for detections. A detailed proof of the Born rule and measurements is beyond the scope of this paper.

However, there are some shortcomings of the current theory which need to be addressed. In the first place, the analysis has been performed under the assumption that the gravitational fields involved are weak and the perturbation around the equilibrium position is small. The exact nature of the vacuum loading regime and the evolution of the field under highly nonlinear conditions require further study. Secondly, the present model utilizes the concept of a scalar field and lacks a full geometric treatment of the problem in the framework of general relativity theory [9][10]. Thus, the main finding of the current paper lies in establishing the dispersion relationship for intrinsic vacuum fluctuations as the core connection between the vacuum microscopic structure and physical laws at large scales. It can be expected that further exploration of the vacuum energy functionals and their nonlinear dynamics will bring us closer to achieving unification of interactions.

References

[1] T. Kumar and Vandana, "Emergent Gravitation and Quantum Wave Dynamics from a Bounded Vacuum," *J. Appl. Math. Phys.*, vol. 14, no. 4, pp. 1308–1333, 2026, doi: https://doi.org/10.4236/jamp.2026.144061.

[2] S. Weinberg, *The quantum theory of fields*, vol. 2. Cambridge university press, 1995.

[3] P. A. M. Dirac, *The principles of quantum mechanics*, no. 27. Oxford university press, 1981.

[4] M. Born, "Quantenmechanik der stoßvorgänge," *Z. Für Phys.*, vol. 38, no. 11, pp. 803–827, 1926.

[5] E. Schrödinger, "An undulatory theory of the mechanics of atoms and molecules," *Phys. Rev.*, vol. 28, no. 6, p. 1049, 1926.

[6] A. Einstein, "The general theory of relativity," in *The meaning of relativity*, Springer, 1922, pp. 54–75.

[7] S. Weinberg, *The quantum theory of fields*, vol. 2. Cambridge university press, 1995.

[8] L. De Broglie, "Recherches sur la théorie des quanta," 1924.

[9] A. Einstein, "The general theory of relativity," in *The meaning of relativity*, Springer, 1922, pp. 54–75.

[10] E. Albert, W. Perrett, and G. Jeffery, "The foundation of the general theory of relativity," *Ann. Phys.*, vol. 354, no. 7, p. 769, 1916.