Completing the quantum ontology with the electromagnetic zero-point field

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Abstract
This text begins with a series of critical considerations on the initial interpretation of quantum phenomena observed in atomic systems. The bewildering explanations advanced during the construction of quantum mechanics are shown to have distanced the new theory from the rest of scientific knowledge, by introducing indeterminism, acausality, nonlocality, and even subjectivism as part of its interpretative framework. The conclusion drawn from this unsatisfactory interpretative landscape is that quantum mechanics lacks a key ontological ingredient. Arguments are given in favour of the random zero-point radiation field (ZPF) as the element needed to complete the quantum ontology. The (wave-mediated) quantum stochastic process is shown to be essentially different from Brownian motion, and more amenable to an analogy with the hydrodynamic case. The new perspective provided by the introduction of the ZPF is used to explain some salient features of quantum systems, such as the stationary atomic states and the transitions between them, and the apparent nonlocality expressed in the entangled states. Notably, the permanent presence of the field drastically affects the dynamics of the (otherwise classical) particle, which eventually falls under the control of the field. This qualitative change is reflected in the transition from the initial classical description in space-time, to the final quantum one in the Hilbert space. The clarification of the mechanism of quantization leads us to consider the possibility that a similar phenomenon occurs in other physical systems of corpuscles subjected to an oscillating background, of which the walking-droplet system is a paradigmatic example.

1 Introduction
A careful study of quantum mechanics (QM) as it is systematically presented and understood in present-day publications, from the dominant Copenhagen perspective or any of the alternatives—which can be counted by the dozen—leads to the conclusion that it must be indeed an incomplete theory. Only an incomplete theory can be ‘completed’ with such a plentiful variety of alternatives, some even in clear contradiction amongst them. But rather than the
incompleteness considered by Einstein —any statistical description is incom-plete by nature—we refer here to an essential ingredient that is missing. This assertion, quite significant for a theory that is considered to be the basis of half (if not more) of modern physics, gets reaffirmed by a critical analysis of the origin of a few of its most representative and fundamental postulates—some implicit, others explicit.

One such postulate that calls for immediate attention is related to the early discovery by Heisenberg of the hazardous motions of the electrons. Being unaware of any known explanation, Heisenberg proposed to consider such motions as a trait of nature and postulated that the electron (as any other quantum particle) has an inherently indeterministic and acausal behaviour. This postulate was blindly accepted by the physics community of the time, and was never subjected to experimental corroboration, not even after the advent of quantum field theory, which inherited it. It is interesting to note that even the community of philosophers of science involved in quantum theory, otherwise so demanding, accepted Heisenberg’s postulate as a significant part of reality. With this step, the phenomenological description—of the save-the-phenomenon type—provided by quantum mechanics was adopted and taken for a fundamental, first-principles construction.

On the other hand, the Schrödinger description and variants thereof contain, either tacitly or explicitly, a nonlocal element that is present in all instances except for the (rather unphysical) case of constant probability density in the entire space. Physicists became accustomed to use (even inadvertently) quantum nonlocality and accept nonlocal behaviour as a quantum trait; of recently this point has taken on increased importance. Being locality a property that is expected of any fundamental physical theory, the conceptual—and philosophical—difficulties with usual quantum theory continued to accumulate.

On top of this, we recall the description of the atom à la Heisenberg as an entity that lives in an abstract, mathematical space—a Hilbert space, a well defined mathematical structure—with no indication at all of what is taking place in real space-time. Such a description leaves us without a meaningful and transparent picture of what the atom is and what its electrons are doing. A further difficulty is related to the introduction of ‘quantum jumps’ between states, which were (and still are, to a large extent) taken as a capricious quantum trait, not amenable to further analysis. Strictly speaking, we rely on a powerful formal description of the atom, with no associated intelligible picture of it.

Despite the fact that the difficulties mentioned here (among others) strongly suggested the need to adopt a statistical perspective of the quantum phenomenon, this possibility was dismissed in general (and adamantly opposed by the Copenhagen school in particular), opening the door to another ineluctable ingredient, the observer. The introduction of this active character in order to ‘explain’ the reduction of the characteristic quantum mixtures to the pure states observed, added a subjective ingredient to the already odd quantum scheme.
2 The missing ingredient

From a narrative as the one just presented, one concludes indeed that, for historical reasons, in the process of construction of quantum mechanics some fundamental ingredient was left aside. The absence of an appropriate ontological element turned the physical situation into a mystery. The missing ingredient being so fundamental, its disclosure should, as a minimum, explain the quantum motions that go under the indeterministic name of quantum fluctuations, as well as the origin of the apparent nonlocality, the existence of stationary states and the spontaneous transitions between them.

Since all atomic constituents, whether charged or not, have an electromagnetic structure, and electromagnetic interactions are ubiquitous in the atomic world, a natural candidate to fill the ontological gap is the random zero-point electromagnetic field (ZPF). This stochastic field was well known since its introduction into the quantum world by Max Planck in 1912 [2], yet it was largely ignored for decades. Taken as a real electromagnetic field that pervades the entire space, one may envisage that any quantum particle with electromagnetic properties is in permanent contact with it and therefore acquires an essentially stochastic motion [3]. In addition, by serving as a bridge that connects the individual particles of a system, this field is expected to induce correlations between their motions even when they do not interact directly, thus leading to an apparently nonlocal behaviour, as is manifested e. g. in quantum entanglement.

More broadly, consideration of the ZPF as a fundamental ontological constituent offers a range of possibilities to explain quantum phenomena. An important one is the fact that the electron extracts energy from the ZPF, which can make up for the loss of energy due to the radiation of the accelerated charge. As noted by Nernst as early as 1916 [4], this may explain a most intriguing and persistent mystery, namely atomic stability: how is it that the electron is permanently radiating, but the atom is stable? What’s more: a precise compensation of the mean energy radiated to the field by the mean energy absorbed from it can take place only for certain very specific orbital motions, offering in principle an explanation of atomic quantization. Simple calculations or estimates taking into account the known properties of the ZPF give support to these conjectures. The theory based on the assumption of the ZPF as an essential ingredient, called stochastic electrodynamics (SED), is not yet fully developed, but it has already produced a variety of positive and promising results ([5]-[8] and references therein).

One important lesson of the theory developed so far is that, as a result of the permanent action of the background field on an otherwise classical particle, a qualitative, irreversible change in the dynamics takes place: the particle ceases to behave classically and acquires properties that are considered inherently quantum [9][10]. The effect of the field is not a mere perturbation, which means that a perturbative approach to the SED problem is doomed to produce erroneous results in general. No perturbative calculation to any order will give rise to a qualitatively different behaviour; the new situation requires a new description. And this is just the quantum one. Briefly: QM ceases to be a
mechanical theory to become an electrodynamic theory.

The introduction by Planck of the zero-point field and its associated energy $E = \frac{\hbar \omega}{2}$ per mode, can be considered as significant and groundbreaking as his introduction of the quantization of the energy $E = \hbar \omega$ interchanged between matter and field, which led him to his famous blackbody formula. On one hand, the zero-point term means a definitive departure from classical electromagnetism by establishing a nonzero energy for the ground state of the field. Further, it provides the basis for an understanding of the quantum phenomenon, as proposed by SED. The fact that the total energy, integrated over the entire range of frequencies from 0 to $\infty$, has an infinite value, has been used as an argument to deny the reality of this field. This problem, however, is not unique to SED; it is shared by quantum theory, which deals with it in the form of vacuum fluctuations. The infinite energy of the vacuum is in fact an open problem for cosmology, and different attempts to solve it can be found in the literature (see e. g. [11]).

In this regard it is worth mentioning the proof by Unruh [12] that the black-hole evaporation process is insensitive to the high-frequency regime. Unruh ascribes this to the time scales involved in the process, which are inversely proportional to the mass of the black hole, hence relatively long compared with Planck or atomic scales, and concludes that 'if the state is the vacuum state at high frequencies, it remains the vacuum.' In SED (as in non-relativistic QM) the particles interact predominantly with modes of low frequencies, whence the high-frequency modes have no effect on the dynamics; particles are essentially transparent to them. Moreover, at frequencies higher than (double) the Compton frequency, relativistic (high-energy) processes such as particle creation and annihilation take place. Therefore in the calculation of (nonrelativistic) radiative corrections, in which the entire spectrum intervenes in principle, it is legitimate to introduce a cutoff at the Compton frequency (as is usually done in nonrelativistic QED).

Coming back to the conceptual, philosophical considerations, we conclude that the mystery and magic that have accompanied the quantum world over decades, may be dissolved in principle by considering the presence of the ZPF as a real, physical field in permanent contact with matter. Its introduction as an inseparable ingredient of the ontology of any quantum system allows us to recover determinism, causality, locality and objectivity. The corollary is that the classical and the quantum worlds are not two distinct, separate worlds, each obeying its own rules; there is a single world in which they coexist.

3 On the nature of quantum stochasticity

A phenomenological theory called stochastic mechanics (alternatively, stochastic quantum mechanics, SQM) was initiated by the mathematician Edward Nelson [13] with the purpose of describing quantum mechanics as a stochastic phenomenon without the need to specify the source of stochasticity. A more general formulation of SQM was developed later, which serves to describe the dynamics
of two distinct types of stochastic process, in the Markov approximation: the classical, Brownian-motion type and the quantum one [14, 7].

An important feature of sQM is the appearance of two (statistical) velocities on an equal footing: the flux (or flow) velocity $v$ and the diffusive (or stochastic) velocity $u$. These basic kinematic elements for the description are obtained by averaging over the ensemble of particles in the neighborhood of $x$ at times close to $t$. When the time interval $\Delta t$ is taken small but different from zero, the two velocities are obtained, namely (see e. g. [13, 7])

$$v(x,t) = \frac{x(t+\Delta t) - x(t-\Delta t)}{2\Delta t} = \hat{D}_c x,$$

(1)

with the systematic derivative operator given by

$$\hat{D}_c = \frac{\partial}{\partial t} + v \cdot \nabla,$$

(2)

and

$$u(x,t) = \frac{x(t+\Delta t) + x(t-\Delta t) - 2x(t)}{2\Delta t} = \hat{D}_s x,$$

(3)

with the stochastic derivative operator given by

$$\hat{D}_s = u \cdot \nabla + D \nabla^2,$$

(4)

and the diffusion coefficient

$$D = \frac{(\Delta x)^2}{2\Delta t},$$

(5)

assumed to be constant. The symbol $\langle \cdot \rangle$ denotes ensemble averaging.

The two time derivatives (2) and (4), applied to the velocities (1) and (3), give rise to four different accelerations, which are used to construct a couple of generic dynamical equations. In the absence of an external electromagnetic field these are the time-reversal invariant generalization of Newton’s Second Law, and the time-reversal non-invariant equation leading to the continuity equation, respectively,

$$m \left( \hat{D}_c v - \lambda \hat{D}_s u \right) = f,$$

(6)

$$m \left( \hat{D}_c u + \hat{D}_s v \right) = 0,$$

(7)

with $\lambda$ a free, real parameter, and $f = -\nabla V$ the external force acting on the particle. Since the magnitude of $\lambda$ can be absorbed into the value of $D$, one takes $\lambda = \pm 1$. The specific dynamical properties of the system strongly depend on the sign of this parameter: $\lambda = -1$ implies an irreversible dynamics, of the Brownian-motion type. By contrast, $\lambda = 1$ implies a reversible stochastic dynamics and leads after some algebra to the Schrödinger-like equation

$$-2mD^2 \nabla^2 \psi(x,t) + V(x) \psi(x,t) = 2imD \frac{\partial \psi(x,t)}{\partial t},$$

(8)

5
and its complex conjugate, where $\psi(x, t)$ is a complex function whose squared modulus is the density distribution

$$\rho(x, t) = |\psi(x, t)|^2,$$

and

$$v = iD \left( \frac{\nabla \psi^*}{\psi^*} - \frac{\nabla \psi}{\psi} \right), \quad u = D \left( \frac{\nabla \psi^*}{\psi^*} + \frac{\nabla \psi}{\psi} \right).$$

The Schrödinger equation proper is obtained from (8) by taking

$$D = \hbar/2m.$$ 

### 3.1 A possible connection with hydrodynamics

By subtracting Eq. (7) from (6) and introducing the access (or backward) velocity, which is the linear combination of the velocities $v$ and $u$

$$v_a = v - u = (D_c - D_s) x,$$

one obtains after some rearrangements

$$\frac{\partial}{\partial t} v_a + v_a \cdot \nabla v_a - D \nabla^2 v_a = -\frac{1}{m} \nabla (V + 2V_Q),$$

where $V_Q$ stands for the quantum potential,

$$V_Q = -\frac{1}{2} m u^2 - mD \nabla \cdot u = -2mD^2 \frac{\nabla^2 \sqrt{\rho}}{\sqrt{\rho}}.$$ 

Incidentally, this equation shows that the quantum potential $V_Q$ is determined by the spatial density $\rho(x, t)$, a function that depends on what is happening in the entire space, and thus contains nonlocal information. Equation (13) corresponds in hydrodynamics to the Navier-Stokes equation for an incompressible, viscous fluid, if $mD$ is taken for the kinematic viscosity $\nu$ and $(V + 2V_Q)/m$ is identified with the total pressure divided by the fluid density $\rho_o$. With this identification, Planck’s constant corresponds to $\hbar \iff 2\rho_o \nu$. Interestingly, however, this is not an equation for the flow velocity $v$ but for the access velocity $v_a$. This velocity represents the coarse time-scale local average of the displacement from time $t - \Delta t$ to time $t$, i. e.,

$$v_a(x) = \frac{\langle x(t) - x(t - \Delta t) \rangle}{\Delta t} = \frac{\langle \Delta_x \rangle}{\Delta t},$$

where the average is taken over the ensemble of particles that cross the point $x$ at time $t$, taking into account that at an earlier time $t - \Delta t$ those particles had a distribution of positions $x' = x(t - \Delta t)$. It should be borne in mind that $\Delta t$ must be much smaller than the characteristic time of the systematic motion, but large enough as to embrace the most closely spaced, rapid changes in $x$. If
the system satisfies an ergodic principle, \( t \) may also represent the different times at which the same particle crosses the point \( x \) again and again.

A question that comes to mind is whether this analogy between the quantum and the hydrodynamic cases can be extended to include the effect of a walking droplet on the fluid and, ultimately, obtain the 'quantumlike' behaviour of the fluid-droplet system [15]. In particular, are the statistics of the horizontal trajectories of walking droplets the equivalent of the quantum statistics represented by \( \rho \), as is suggested in several papers on the subject?

For a system composed of a fluid layer acted on by a vibrating force and by the bouncing droplet, the total pressure appearing in the Navier-Stokes equation must include the external pressure \( P \) on the fluid surface due to the bouncing droplet, and the gravity term \( g \) must include the effective acceleration due to the vibrations, \( g(t) = g + \gamma(t) \). Further, the resulting Navier-Stokes equation has to be complemented with the equation of motion for the droplet under the action of the fluid. Since with each bouncing, the droplet pressure on the fluid surface modifies the value of \( h(x) \), and the dynamics of the droplet depends in its turn on the force exerted upon it by the modified fluid surface, one ends up with a coupled, nonlinear system of equations that is difficult to analyze with a view to establishing a (direct) comparison with SQM, viz. QM.

The accumulated memory effects on the wave field, and the dependence of the droplet-fluid interaction on the relative phase and varying shape of the fluid surface during contact, seem to be essential points to consider in this regard. The first of these suggests focusing on hydrodynamic analogs of the stationary states in quantum mechanics, when the wave field has become stabilized and a well-defined histogram of the droplet positions is obtained. The second point suggests introducing a random element in the description of the horizontal motions, which could serve to bring to the surface the counterpart of the diffusion coefficient of SQM – or equivalently, of the stochastic velocity \( u \). It seems to us of considerable importance that \( u \) may acquire values comparable to those of \( v \).

To give precision to the above considerations, we rewrite Eq. (13) in the form

\[
\frac{Dv_n}{Dt} = -\frac{1}{m} \nabla (V - mD \nabla \cdot v_n + 2VQ).
\] (16)

This equation, which is just another form of the Schrödinger equation, offers a statistical description of the moving quantum particles of the problem under scrutiny, the analog of the droplets. We should then perhaps reconsider our previous ‘hydrodynamic’ point of view and take equation (16), and thus (18), as the quantum equivalent (or analog) of Newton’s equation of motion for the walking droplets. The mean local force acting on the droplets contains then, in addition to the expected classical components, a term similar to the quantum potential with its associated nonlocality.
4 The wave element in SED

A usual starting point for the analysis of the particle dynamics in SED is the (nonrelativistic) equation of motion, known as Braffort-Marshall equation

\[ m\ddot{x} = f(x) + mτ\dot{x} + eE(t), \]  

(17)

where \( mτ\dot{x} \) stands for the radiation reaction force, with \( τ = \frac{2e^2}{3mc^3} \). For an electron, \( τ \approx 10^{-23} \) s. \( E(t) \) represents the electric component of the zpf taken in the long-wavelength approximation, with time correlation given in the continuum limit by \((j,k = 1,2,3)\)

\[ \langle E_k(s)E_j(t) \rangle = δ_{kj}\varphi(t - s), \]  

(18a)

where the spectral function

\[ \varphi(t - s) = \frac{2\hbar}{3πc^4} \int_0^∞ dωω^3 \cos(ω(t - s)) \]  

(18b)

corresponds to an energy \( \hbarω/2 \) per mode. This establishes a crucial distinction between classical, Brownian-type processes, governed by a white noise, and the present stochastic process which is governed by a stationary, correlated (wave) field with a highly coloured spectrum.

A statistical treatment of the one-particle problem, starting from Eq. (17) and involving the construction of a generalized Fokker-Planck equation, has been shown to lead in the radiationless approximation to the Schrödinger equation [16, 8]: this is the approximation that corresponds to quantum mechanics. The stationary states are obtained as the solutions that satisfy the energy-balance condition, as predicted by Nernst over a century ago. When the radiative terms are not neglected, the theory reproduces in addition the corresponding corrections in coincidence with non-relativistic quantum electrodynamics [17, 8]. In particular, the formulas for the radiative lifetimes are obtained for the excited states that in the Schrödinger approximation appear as stationary.

Interestingly, in the process leading to the Schrödinger equation via the Fokker-Planck equation, which focuses on the statistical properties of the dynamics, the wave element is not conspicuous; it remains as concealed as in SQM. Yet the zpf eventually leaves its indelible mark through the appearance of Planck’s constant in the Schrödinger ‘wave’ equation.

An alternative route followed in a subsequent development of SED, called linear stochastic electrodynamics (LSED), takes us to the quantum equations in its matrix formulation ([8]; see also [9, 10] for more recent work). As is well known, the wave element is absent from the final (Heisenberg) equations, which have a purely mechanical aspect. However, in the SED process leading to these equations (see section 5 below), the relevant field modes with which the particle interacts appear explicitly. This allows us to investigate the role played by such field modes when two (not directly interacting) identical particles are simultaneously connected to them. As a result, the entanglement of particles finds an
explanation in the correlation between their motions established through the common field modes \cite{13,18}. In this regard, it is appropriate to mention the connection with the hydrodynamic work by Borghesi et al \cite{19}, who investigate experimentally the energy stored in the wave field for two coupled walking droplets and how it conveys an interaction between them. More generally, the observation that the background field acts as a bridge between particles has important consequences for the statistics of (identical) quantum particles.

4.1 Compton’s frequency revindicated

In de Broglie’s pioneering work on wave mechanics, the Compton frequency is well known to have played a key role as the frequency of the particle’s internal clock. (Later it was understood by some that de Broglie’s wavelength has actually a statistical meaning.) Nevertheless, the nature of the associated wave in de Broglie’s theory, which was basic for the development of Schrödinger’s theory, was left unidentified by de Broglie, and in fact it remains to date concealed at the core of the foundations of quantum mechanics.

A variety of recent works, both theoretical and experimental, point to a revival of the internal clock conjectured by de Broglie, which in turn may have an important impact on our understanding of the quantum phenomenon. Among such works we have on one hand a series of experiments in which high-energy electron beams are channelled through silicon crystals \cite{20,21}, providing evidence of a resonance suggestive of de Broglie’s clock. Ironically, these findings have received apparently almost no attention, except for an essay by Hestenes \cite{22} and a Monte-Carlo-based analysis by Bauer \cite{23} showing consistency with Dirac’s description of the free particle.

On the other hand there is a growing series of both experimental and theoretical work carried out in the field of bouncing droplets referred to above \cite{15}, in which a high-frequency vibration —somehow parallel to de Broglie’s clock— is shown to play a central role in producing phenomena that suggest a hydrodynamic quantum analogy. Also in other fields of physics, high-frequency vibrations imposed on a material system seem to have an important influence, inducing qualitative changes in the dynamics of the system. Worth mentioning are a couple of recent extensions to a generic elastic system with a bead \cite{24}, where also the internal clock of high frequency appears as a key ingredient.

De Broglie’s frequency has had occasional appearances in SED. A first attempt to establish contact with it is the work by Surdin \cite{25} where the electromagnetic nature of de Broglie’s wave is specified as follows from SED, and some experiments dealing with interference and diffraction of neutrons are considered. In \cite{7,8} we present a preliminary view on the functioning of the modes of the ZPF of Compton’s frequency, and their relation to de Broglie’s clock, with a few simple but interesting results. In dealing with some quantum problems within the SED framework we have been induced to introduce, as an ancillary step, a revised version of de Broglie’s idea, appropriately updated in accordance with the demands of SED, which means assigning an electromagnetic nature to the de Broglie wave. In the process leading to the appearance of de Broglie’s wave,
the assumption of a resonant interaction of the electron with the ZPF modes of Compton’s frequency has been the starting point. Essentially this amounts to distinguishing the modes of the ZPF of Compton’s frequency from the rest of the field.

More recently, we have put forward an estimate of the duration of a transition between atomic states—the infamous quantum jumps—based on the assumption that the transition is triggered precisely by a resonance of the atomic electron with modes of the zero-point radiation field of Compton’s frequency [26]. The theoretical result, given essentially by the expression \((\alpha \omega_C)^{-1}\), where \(\alpha \sim 1/137\) is the fine structure constant and \(\omega_C\) the Compton angular frequency for the electron, lies well within the range of the experimentally estimated values, which is of the order of attoseconds \((10^{-18} \text{ s})\) [27, 28]. Incidentally, one can still come across articles negating quantum transitions, in adherence to Bohr’s dictum—and any other kind of apparent discontinuities, for that matter (e.g. [29])—or taking them as a sudden increase of our knowledge of the system (e.g., [30, 31]) rather than a physical phenomenon.

5 On the classical-to-quantum transition

The transition from the classical to the quantum regime represents a most delicate point of the emerging-quantum theory. A detailed account of the dynamics leading to quantization, and of the conditions under which quantization is obtained, is still a pending task, although some important steps have been achieved.

Notably, by applying a Hamiltonian treatment to the composite (initially noninteracting) particle-field system, it is possible to show that in the classical-to-quantum transition, the field takes control of the response of the particle. As a result of the interplay of stochasticity and dissipation, the particle loses memory of its initial conditions and ends up responding linearly and resonantly to a well-defined set of field modes, which depends in each instance on the specific problem (i.e., on the external forces acting on the particle) [9, 10]. In the new situation the dynamics is no longer described by the phase-space mechanical variables, but by the coefficients of the response of the particle to those field modes. The response coefficients turn out to be nothing less than the matrix elements of the operators \(\hat{x}\) and \(\hat{p}\), which satisfy the basic quantum commutator \([\hat{x}, \hat{p}] = i\hbar\), just as was advanced by Heisenberg in his pioneering work on quantum mechanics [32]; this reflects the fact that the Hamiltonian evolution preserves the original symplectic structure.

The Hilbert-space formalism represents thus a compact and elegant way of describing the response of the particle to a set of (relevant) field modes once the quantum regime has been attained, at the cost of a space-time description of what is really happening inside the atom. Interestingly, the field has disappeared once more from the picture, this time leaving its indelible mark through the appearance of Planck’s constant in the basic commutator.

It should be noted that prior to the onset of the quantum regime, the dynam-
ics is irreversible and memory accumulates in the near background field, which is an indication of a highly non-Markovian process. In the quantum regime, by contrast, the stochastic process is Markovian, the Markovianity referring to the loss of memory between quantum-mechanical processes such as atomic transitions. This feature is related with the times involved in the description: we recall from section 3 that the time interval $\Delta t$ introduced in SQM to derive the QM equations entails a statistical coarse-grain description of the dynamics. The minimum times involved in (non-relativistic) QM are smaller than the orbital periods and the lifetimes of excited states, but certainly larger than the inverse of the Compton (or Zitterbewegung) frequency, or even the time involved in a 'quantum jump' (which as discussed above, is an estimated 100 times larger than the Compton time). For this reason, QM as we know it is unable to describe with a sufficiently high resolution in time the trajectories of particles, transitions between states, or other continuous processes.

6 Final comments

The experience with SED, as illustrated by the results discussed in the preceding sections, is that the main features characteristic of quantum-mechanical systems emerge from the permanent interaction of the random zero-point radiation field with matter; for this reason it can be said that QM is an emergent theory. By adding the ZPF to the quantum ontology, a physically coherent, local and objective picture of the quantum phenomenon is obtained, free of ad-hoc postulates and mysterious elements.

It seems hard to rule out the possibility that analogous quantization phenomena take place in other realms of physics, in which a stationary, vibrating background acts permanently on one or more corpuscles. The (hydrodynamic) walking-droplet system and the (electrodynamic) atomic-matter system are perhaps two prominent examples of a more general phenomenon with interesting ramifications. It remains to be seen whether a common ground can be found that allows us to deepen our mutual learning, further identify commonalities, and establish the extent of the analogies, for the benefit of a more comprehensive, satisfactory understanding of the quantum phenomenon.

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