# THE STOCHASTIC FOUNDATIONS OF QUANTUM MECHANICS*

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ABSTRACT: After pointing out that important unresolved problems concerning the basis of quantum mechanics still exist and briefly mentioning some relevant earlier attempts to remove them, this paper outlines a recently developed theory which establishes a foundation for quantum mechanics in stochastic theory. In contrast with previous work, this is done by developing a description which covers quantum and classical stochastic processes and thus shows up both their similarities and their differences. This theory contains two parameters, the diffusion coefficient $D$ and a quantity $\lambda$ whose sign determines the type of stochastic process. To give values to these parameters, a physical picture for the medium underlying the stochastic process is required. In the second part of the paper this is provided by the fluctuating electromagnetic vacuum of stochastic electrodynamics. The behaviour of a harmonic oscillator in this field is studied; a

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finite solution to the problem is found and shown to behave in the equilibrium limit like a quantum harmonic oscillator; the solution satisfies the equations of the stochastic theory outlined in the first part of the paper only if the parameters $D$ and $\lambda$ have their quantum-mechanical values. A non-relativistic Lamb shift and radiative mass correction for the electron are also derived without any divergent integrals nor any need for renormalisation; these have physically meaningful values.

Certainly nobody doubts that modern quantum mechanics is a firmly established theory. However, it is also true that despite its enormous successes it requires to be revised from its very foundations if we want to understand the origin of the difficulties which afflict it today.

The difficulties of quantum theory are not only its divergencies; in fact it has been dragging along conceptual difficulties since it was born. It suffices to analyze critically a series of textbooks on the subject, to convince oneself that the confusion that prevailed during the foundation and construction of wave mechanics in the 20's and 30's has not disappeared; it is present in the books which we used yesterday to learn and those we use today to teach.

Our knowledge about the theory and its structure; the successful application of its methods to complex problems, and the familiarity and the confidence which we have gained through its daily use, usually lead us to a stage in which the conceptual difficulties which might have troubled us in the beginning disappear forever. But by neglecting a problem we do not solve it, quite the contrary.

That these problems are real and complex, and not simply digressions of idle minds, is evident from the long and sometimes bitter and fruitless discussions held between Einstein, Bohr, Born[1] and so many others, during which serious and profound discrepancies came to light. Many questions about quantum mechanics remain unsettled to the present time, and despite their fundamental character, some of them are given the most diverse and even contradictory answers by the physicists. Let us raise a few questions to illustrate the point.

Is the motion of an electron causal? If the answer is in the negative, then what is it that constrains the electron to follow well-defined laws which contain more than merely random components? And through which mechanism?

If, on the other hand, the motion is causal, what produces the random behaviour of the electron?

Is the quantum mechanical description objective? On the one hand, if the observer and his mental state constitute necessary elements of the system, then why doesn't there exist any specific mathematical element that corresponds to them in the theory?

If, however, the description is objective, then why do we make it in terms of observables and observers?

We can further ask: Does quantum mechanics provide a complete description of reality? If the description is complete, why can't we predict, for instance, the time of disintegration of a nucleus, though we may determine it experimentally? Or are we dealing with a complete theory that can furnish only some experimental results?

If the description is the most complete ever feasible, what is it that limits our capacity to inquire further into the physical world?

If, on the other hand, the description is not complete, then what does it lack and what else should it contain?

We shall not enlarge this list of interrogations. The interesting point is that the answer that quantum mechanics gives to each of these questions is not unique, but is specific for a certain current of thought. Even more: there are physicists for whom some of these questions are meaningless, while in the view of others a definite answer is essential. Under these circunstances one might almost raise a further question, namely: Is this wide conceptual uncertainty of contemporary quantum mechanics perhaps one more manifestation of the uncertainty relations? Perhaps there are some who would even assert, so as not to violate the uncertainty relations, that the only thing we know for certain is "who knows?".

Let us now go over to the subject of our paper. A few years after the foundations of modern quantum mechanics were laid by Heisenberg, Schrödinger, Dirac, etc., there appeared the first attempts to revise this newborn and highly successful theory. One of the directions that began to develop and that is of direct interest for our work, was inaugurated by Fürth[2], who proposed to interpret the quantum process as a diffusion, motivated mainly by relatively obvious mathematical analogies and by the statistical character of quantum predictions. Later on, Fényes[3] proposed a stochastic theory in which he could derive the Schrödinger equation from a hydrodynamic Lagrangian constructed ***ad hoc***. This line of thought was continued by Weizel[4] and others, but its scarce success caused it to decline.

The idea was resurrected subsequently, in analogous physical terms but with the help of more developed techniques. Kershaw[5], for instance, is able to derive the stationary Schrödinger equation by postulating that the path of the electron is a classical path altered by a fluctuating movement. Approaches of this kind are no doubt interesting, in that they represent attempts to achieve a more fundamental description of the behaviour of the electron; however, they all suffer from the habit of reducing the quantum phenomenon with all its peculiarities to a classical stochastic process. This helps create a major confusion as it obscures the distinction between the movement of an electron and that of a colloidal particle, for example.

In spite of these shortcomings, the very idea of a stochastic process underlying quantum mechanics proves fertile; attempts along this line have appeared without interruption in the last few years. It is not our intention to present to you a comprehensive list of the numerous contributions on this theme; however, it is relevant to recall here the work by Nelson[6], probably the best known at present. From the theory of Uhlenbeck and Ornstein, which describes a stochastic process in phase space, Nelson obtains a dynamical relation which he then transfers to configuration space, to derive from it the Schrödinger equation. In our view, the most important aspect of Nelson's contribution is that he shows that the quantum stochastic process is not reducible to any of the classical stochastic processes, because he is obliged to combine in a somewhat arbitrary way two descriptions which are valid in different classical situations, in order to obtain quantum results.

Subsequent to Nelson's works there have appeared other formulations that imply or are consistent with this basic principle, though they develop it along different lines[7]. Under these circumstances the question arises of whether it is possible to construct a theory for stochastic corpuscles of sufficient generality as to include in a natural way the quantum movement. The fact that this question can be answered in the affirmative[8], as we shall see below, allows us to conclude that quantum mechanics can be understood as a *sui generis* stochastic process, different and distinguishable from those characterizing classical phenomena such as Brownian movement. Consequently the statistical content of quantum mechanics is to some degree analogous to that of the theory of Brownian movement, though the two theories differ essentially in their dynamical detail.

Hence, we must face a further question, namely: what is the origin of quantum stochasticity? As we shall see in the second part of this paper there are reasons to suppose that the cause of stochasticity may be found in the interaction of the electron with a fluctuating electromagnetic field, whose "vacuum" state is analogous to the vacuum field of quantum electrodynamics. This sort of answer would have the additional advantage of determining a physically real equivalent for a necessary theoretical element such as the zero-point radiation field, thus corroborating the possibility of constructing a consistent theory for the system composed of the electron and the electromagnetic field*.

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*It should be stressed that the introduction of a real fluctuating field with an energy per normal mode of $\frac{1}{2}\hbar\omega$ is not free from considerable and still unsolved difficulties; this is an open question and here we merely acknowledge its existence.

Within a scheme of this sort, the radiative corrections, for instance, which are proper to quantum electrodynamics, arise naturally by taking into account the interplay between the (stochastic) Lorentz force and the radiation reaction[9]. Other quantum phenomena find a natural explanation as well: for instance the interference phenomena of quantum mechanics may be understood as the form in which the properties of the background field are reflected upon the movement of the particles coupled with it.

The formulation of stochastic quantum mechanics which we are referring to goes roughly as follows[8,10]: it starts by developing a statistical description for a general stochastic process in coordinate space. To this end we construct first the kinematics for the stochastic process, in terms of quasi-local dynamical variables, which are already statistical quantities obtained by considering an ensemble of systems characterized by a density $\rho(\mathbf{r},t)$. Thus we arrive at two different concepts of velocity: the systematic or flux velocity $\mathbf{v}$ and the stochastic or diffusion velocity $\mathbf{u}$, which can be written as

$$\mathbf{v} = \mathcal{D}_c \mathbf{r}, \qquad \mathbf{u} = \mathcal{D}_s \mathbf{r} \tag{1}$$

where

$$\mathcal{D}_c = (\partial/\partial t) + \mathbf{v}\cdot\nabla, \qquad \mathcal{D}_s = \mathbf{u}\cdot\nabla + D\nabla^2 \tag{2}$$

are the systematic and the stochastic derivative operators respectively. The "diffusion coefficient" $D$ is (one half of) the second derivate moment of $r_i$. It is possible to prove further that

$$\mathbf{u} = D\nabla\rho/\rho. \tag{3}$$

In an analogous way we can define four different accelerations:

$$\mathcal{D}_c\mathbf{v},\ \mathcal{D}_s\mathbf{u},\ \mathcal{D}_c\mathbf{u},\ \mathcal{D}_s\mathbf{v}.$$

We use these elements to construct two dynamical equations that describe the statistical behaviour of the system: an equation of motion and a continuity condition. In constructing the first one, we are guided by the corresponding dynamical equation, which is assumed to have the form of a general Langevin-type equation:

$$m\ddot{\mathbf{r}} = \mathbf{f}_{\text{ext}} + \mathbf{f}_{\text{dis}} + \mathbf{f}_{\text{stoch}} \tag{4}$$

where $f_{ext}$ is the external force, $f_{dis}$ is the dissipative part of the force that arises as a result of the interaction between the particle and the stochastic medium and $f_{stoch}$ is the purely random part of this force.

The corresponding average equation is therefore a relation between the average force and a linear combination of the four accelerations introduced previously. But by taking into account first that all terms must have the same behaviour upon time reversal, and second that in the non-stochastic limit (i.e., when $\mathbf{u} \to 0$) the equation should reduce to Newton's second law, we are left with

$$m(\mathcal{D}_c \mathbf{v} - \lambda \mathcal{D}_s \mathbf{u}) = \mathbf{F}^+ \tag{5}$$

as the equation of motion. $\lambda$ is a real, but otherwise arbitrary parameter, and $\mathbf{F}^+$ is the force term that does not change its sign upon time reversal.

The second dynamical equation is the stochastic version of the equation of continuity:

$$m(\mathcal{D}_s \mathbf{v} + \mathcal{D}_c \mathbf{u}) = \mathbf{F}^- \tag{6}$$

with

$$\mathbf{F}^- = -m(\mathbf{u} \times \nabla \times \mathbf{v} + D\nabla \times \nabla \times \mathbf{v}). \tag{7}$$

In fact, the continuity equation is derived by introducing Eqs. (3) and (7) into (6) and integrating over the space coordinates.

Eqs. (5) and (6) can be combined into the suggestive form

$$m\mathcal{D}_q \mathbf{v}_q = \mathbf{F}_q. \tag{8}$$

As we shall see later on, this is the generalization of Newton's second law for classical as well as for quantum systems. Here,

$$\mathcal{D}_q = \mathcal{D}_c + \epsilon \mathcal{D}_s, \qquad \mathbf{v}_q = \mathbf{v} + \epsilon \mathbf{u}, \qquad \mathbf{F}_q = \mathbf{F}^+ + \epsilon \mathbf{F}^- \tag{9}$$

and

$$\epsilon = \pm \sqrt{-\lambda}\,.$$

We shall assume that the dissipative term is small and hence can be introduced later on as a perturbation. When the force is derivable from a potential, Eq. (8) is integrated simply by writing $\mathbf{v}_q$ as a gradient; in the more general case in which there is also an electromagnetic field present, the integration is carried out by introducing the ansatz

$$\mathbf{v}_q = 2\epsilon D\nabla w - (e/mc)\,\mathbf{A} \tag{10}$$

where $w_\pm$ are dimensionless functions and $\mathbf{A}$ is the electromagnetic vector potential; $\mathbf{F}^+$ must now be the Lorentz force. Upon the change of variable

$$\psi_\pm = \exp w_\pm \tag{11}$$

the result of the integration takes the form

$$\mp 2mD\sqrt{-\lambda}\,(\partial\psi_\pm/\partial t) = (1/2m)\,[\pm 2mD\sqrt{-\lambda}\,\nabla - (e/c)\,\mathbf{A}]^2\,\psi_\pm + V\psi_\pm\,. \tag{12}$$

This equation coincides with the Schrödinger equation if we take $\lambda = 1$ and $D = \hbar/2m$.

We would like to add that with $\lambda = -1$, Eq. (12) represents an alternative way of describing Brownian motion, as has been shown elsewhere[8,11]. In this case, however, one must explicitly take into account the frictional force $\mathbf{f}_{dis} = -m\beta\dot{\mathbf{r}}$, which contributes to the potential $V$ in Eq. (12) with the term $-2mD\beta\psi_\pm \ln\psi_+$ (see the second paper in ref. 8). Hence for the classical system we obtain a non-linear Schrödinger-type equation. So we have here a simple method to deal with classical as well as quantum mechanical systems. Clearly, the parallelism between these two systems can be exploited along several directions. For instance, it is possible to work out the path integral methods of Feynman and Kac for quantum mechanical and classical systems, or even a theory of canonical transformations, by using Eqs. (5) and (6) as a starting point.[12]

To obtain the fundamental equation of quantum mechanics we have had to assign certain values to the parameters $\lambda$ and $D$. It is evident that these parameters are related to the specific form in which the particle interacts with the medium that impresses the stochasticity upon its movement; hence, as long as we do not know anything about this medium we cannot derive $\lambda$ and $D$ from first principles.

Let us therefore inquire into the possibility of constructing a specific theory of the general type proposed, by postulating a concrete equation of the form (4).[13] To be consistent with quantum mechanics, this formulation should satisfy two requirements: it should allow for the existence of states of stochastic equilibrium and it should not imply the existence of an absolute reference system.

The most immediate possibility of constructing such a formulation is opened up by the so-called stochastic electrodynamics. The basic hypothesis of this theory[14,15] is the existence of a fluctuating, stationary, Gaussian electromagnetic field whose vacuum state has exactly the spectral energy density of the zero-point radiation field. If we include the radiative reaction force $m\tau\dddot{x}$, which allows us to satisfy both requirements mentioned above, the equation of motion for each electron reads (in one dimension)

$$m\ddot{x} = f + m\tau\dddot{x} + eE(t); \quad \tau = 2e^2/3mc^3 \tag{13}$$

in the nonrelativistic (dipole) approximation. $E(t)$ is the stochastic electric field, whose average is zero and whose correlation function is

$$\langle E(t)E(t')\rangle = \tfrac{2}{3}\pi \int_{-\infty}^{\infty} \rho(\omega)\exp[i\omega(t-t')]\,d\omega \tag{14}$$

or in terms of its Fourier transform

$$\langle E(\omega)E^*(\omega')\rangle = \tfrac{2}{3}\,\pi\,\rho(\omega)\;\delta(\omega-\omega') \tag{15}$$

where $\rho(\omega)$ is the spectral energy-density. To study the ground state of the quantum system we assume $\rho(\omega)$ equal to the energy density of the zero-point field, namely,

$$\rho(\omega) = \hbar\omega^3/(2\pi^2c^3). \tag{16}$$

$E(t)$ is a stationary Gaussian process, but since its correlation function is not an exponential, it is not a Markov process, as follows from Doob's theorem.

We would like to find the statistical solution to the problem defined by Eq. (13), but there are no techniques to solve such a general problem. Seeing that we must content ourselves with tackling particular problems, we choose the harmonic oscillator, which has been partly studied by different authors of stochastic electrodynamics[14]. Therefore, the equation to be solved is

$$\ddot{x} + \omega_0^2 x = \tau\dddot{x} + (e/m)E(t). \tag{17}$$

A solution that is both causal and free from run-away difficulties is

$$x = (e/m)\int_{-\infty}^{\infty}(E(\omega)/\Delta)[(1+2\,\tau\sigma + i\tau\omega)\exp(i\omega t) + G(\omega)\exp(-\sigma t)]\,d\omega \tag{18}$$

where

$$\Delta = [(1+2\tau\sigma)^2 + \tau^2\omega^2]\,[\omega_1^2 + (\sigma + i\omega)^2],$$

$$\sigma = \tfrac{1}{2}\tau\omega_0^2 > 0\,, \quad \omega_1^2 = \omega_0^2 + O(\sigma^2)$$

and $G(\omega)$ is an oscillating function of time. Hence, for large times the last term in Eq. (18) vanishes and the system becomes stabilized. By calculating the energy with the usual formulae, we conclude that the energy acquired by the oscillator due to the action of the fluctuating forces is, to first order in $\tau$,

$$E = \tfrac{1}{2}\hbar\omega_0\,[1 + (\tau\omega_0/\pi)(3\,\ln(1/\tau\omega_0) - 1)] \tag{19}$$

Furthermore, using Eqs. (15) and (18) we can calculate the moments of $x$ and convince ourselves that the corresponding distribution is Gaussian:

$$\rho(x,t) = (1/\sqrt{2\pi\overline{x^2}})\exp(-x^2/2\overline{x^2}). \tag{20}$$

The variance is a complicated function of time which goes to

$$\overline{x^2} = \hbar/2m\omega_0 \qquad (\sigma t \gg 1). \tag{21}$$

These results show that the system behaves just like a quantum harmonic oscillator in its ground state after equilibrium has set in, i.e., for a time $t \gg \sigma^{-1}$ which we can estimate to be of the order of $10^{-15}$ s if the energy is not too low. To show that this coincidence of results is not simply an accident we can try to prove that the statistical description of the stochastic oscillator, once in equilibrium, is given precisely by the Schrödinger equation. The easiest way of doing this is by calculating the velocities $v$ and $u$ from Eqs. (18) and (20). The results are

$$u = -(D/\overline{x^2})\,x \tag{22}$$

and

$$v = -gu\,; \quad g = (1/2D)\,d\overline{x^2}/dt\,. \tag{23}$$

To calculate $u$ we used the formula $u = D\nabla\rho/\rho$ and to calculate $v$ we integrated the equation of continuity.

Now, we note that since Eq. (17) is a particular case of Eq. (4), it should be possible to describe the harmonic oscillator of stochastic electrodynamics by means of the equations of our stochastic formulation. In fact, by substituting $v$ and $u$ we find that

$$m(\mathcal{D}_c v - \lambda \mathcal{D}_s u) = -[mD/(\overline{x^2})^2]\,[D(g^2+\lambda) - g\overline{x^2}]\,x \longrightarrow \lambda(2mD/\hbar)^2\,F_{ext}\,;$$

$$F_{ext} = -m\omega_0^2\,x\,. \tag{24}$$

Hence, once the system reaches equilibrium, it satisfies the equations of the stochastic theory if and only if (cf. Eq. (5) with $F^+ = F_{ext}$)

$$\lambda = 1\,, \qquad D = \hbar/2m\,,$$

i.e., only if the free parameters assume the values that characterize a quantum stochastic system. No negative value of $\lambda$ is consistent with the theory. Hence we conclude that Eq. (17) together with the statistical properties assigned to $E(t)$ refer not to a classical, but to a quantum-mechanical system that is governed by the Schrödinger equation once it reaches equilibrium.

Without going into details for lack of time, we must indicate that the above conclusions can be extended to include the excited states of the harmonic oscillator.

Now it seems appropriate to return to some of the preceding results. In the first place, we observe that the correction to the energy in Eq. (19) is due to the radiation reaction and hence should be identified with the Lamb shift of the harmonic oscillator. To a first approximation, the value obtained is

$$\delta E_\infty = (\alpha\hbar^2\omega_0^2/\pi mc^2)\ln(3mc^2/2\alpha\hbar\omega_0) \tag{25}$$

and compares favourably with the quantum-electrodynamical result, even though we have not introduced relativistic considerations. Most important of all is the fact that there is no need to renormalize, because the integrals involved are convergent. The numerical result is improved by introducing a relativistic cut-off frequency of order $mc^2/\hbar$; in fact, we obtain precisely the value for the Lamb shift predicted by semirelativistic quantum electrodynamics, namely,

$$\delta E_{\omega_c} = (\alpha\hbar^2\omega_0^2/\pi mc^2)\ln(mc^2/\hbar\omega_0)\,. \tag{26}$$

Moreover, by taking $\omega_0 = 0$ we also obtain a finite result for the mass correction of the free particle; if we introduce the same cut-off frequency as before, we get

$$\delta m = (\alpha/6\pi)m\,. \tag{27}$$

We would like to stress that the physically appropriate solution of

Eq. (17) implies a certain modification of the field due to its coupling with the oscillator. This means that the field is modified by the presence of the material system, and acquires a structure which in turn becomes manifest through the statistical behaviour of the system. Here we have a plausible explanation for the wavelike phenomena that are displayed by an ensemble of quantum systems. A further fundamental property of quantum mechanics, namely the superposition of amplitudes, finds a simple explanation in our scheme; in fact, from Eq. (12) we learn that superposition of amplitudes is the rule provided the dissipative forces can be neglected in the process of integration. This happens to be the case in quantum mechanics, due to the smallness of the coefficient $\tau$, but does not occur for a colloidal particle, for instance.

Since there are no reasons to suppose that the harmonic oscillator is the only system of stochastic electrodynamics that has a quantum mechanical behaviour, we are led to believe that our observations are of a more general validity. Although it is true that we have not yet established a direct connection between the fundamental dynamical equations and the statistical equations, the results obtained up to now lead us to believe that this connection exists; that we are not simply being misled by a formal analogy, or even less by a mathematical artifact.

Of course, many questions remain unanswered and many new ones have arisen. We would like to mention only some of them. First, we have described quantum mechanics as a stochastic process in configuration space. Will it be possible to extend the description to phase space and thus construct a theory that would apply for arbitrarily small time intervals? Second, we have assumed that the particle interacts with the radiation field through its electric charge; will it be possible to extend the treatment to neutral particles? In both cases, the answers seem to be in the affirmative, but clearly much work must be done in order to find the final answer.

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## RESUMEN

Después de señalar varios problemas referentes a la fundamentación de la mecánica cuántica, y de mencionar algunos de los intentos más significativos que han aparecido hasta la fecha para resolver dichos problemas, se reseña en este trabajo una teoría recientemente desarrollada, que establece una fundamentación estocástica para la mecánica cuántica. En contraste con las teorías usuales, la descripción aquí desarrollada es aplicable a procesos estocásticos tanto clásicos como cuánticos, y por lo tanto nos permite delinear tanto las similitudes como las diferencias entre ambos tipos de procesos. La teoría contiene dos parámetros: un coeficiente de difusión $D$ y un parámetro $\lambda$ cuyo signo determina el tipo de proceso estocástico. Para asignar valores a estos parámetros se requiere una definición física del medio subyacente al proceso estocástico. En la segunda parte del trabajo se propone que este medio es el vacío electromagnético fluctuante de la electrodinámica estocástica. Se estudia el comportamiento de un oscilador armónico en este campo; se demuestra que este sistema se comporta en el límite de equilibrio como un oscilador armónico cuántico; la solución obtenida satisface las ecuaciones de la teoría estocástica presentada en la primera parte del trabajo si y sólo si a los parámetros $D$ y $\lambda$ se les asignan los valores cuánticos. Por último, se presentan cálculos no relativistas del efecto Lamb y de la corrección radiativa de la masa del electrón, cuyos resultados son finitos y físicamente significativos.