Chapter 10
Quantum Mechanics: Some Answers

Nothing in Nature is random.... A thing appears random only through the incompleteness of our knowledge.

Spinoza (2005)

10.1 The Genetic Gist of the Zero-Point Field

Our investigations started with a recurrent theme of SED, namely the consideration of the fluctuating zero-point radiation field as a basis to arrive at the Planck distribution for the thermal equilibrium radiation field. The quantum of energy introduced by Planck to obtain his law was not a necessary hypothesis[1]; instead, the essential ingredient turned out to be the zero-point component of the field—just the one that Planck discovered in his 1912 paper. This second discovery by Planck acquires, from the present perspective, an importance at least as high as his first one.

The cornerstone for this remarkable result is shown to be contained already in Wien's law, which opens the door to the ZPF—traditionally put aside as an article of faith—by allowing the zero-point energy $\mathcal{E}_0$ of the field oscillators to be different from zero. The conventional (classical) selection $\mathcal{E}_0 = 0$ is clearly unfit for the complexity of a physical world full of electric charges, following all kinds of unending motions and constantly emitting radiation. One should expect in advance the physical reality of the random zero-point field to lead to a statistical behavior of submicroscopic matter that departs from the classical one. And indeed, the presence of this ZPF in an otherwise classical system turns out to radically transform its behavior, leading to the

[1] Something similar happens with the photoelectric effect. This just was the example that Einstein 1905 used to argue in favor of the quantun of radiation. But it is a matter of fact that the cause of this effect can be attributed to the quantization of matter (see e.g. Schiff 1955, Chap. X; Lamb and Scully 1969; Mandel 1976).

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quantization not only of the energy of the field oscillators in interaction with matter, but also to that of matter in interaction with the field, under appropriate conditions.

The specific properties of this background field have very much to do with the peculiarities of quantum systems; they are, so to say, the ultimate source of 'quantum weirdness'. First, the wave nature of the ZPF is responsible for a fundamental difference between the effects of this field on matter and those of an incoherent source of white noise, characteristic of classical, dissipative, Brownian-motion systems—as already anticipated in Chap. 2. A number of results obtained in Chap. 4 through 9 show that a field with highly (spatially and temporally) coherent independent modes, gives rise to an entirely different behavior of the system. Further to leading to nondissipative states and sustaining them—a property remarkable by itself, being at the root of the atomic stability as envisaged by Nernst—it impresses on the mechanical system the 'wavelike' properties encoded in the Schrödinger equation. Moreover, as shown in Chap. 6, the two degrees of polarization of the ZPF modes induce helicoidal motions of the electron, giving rise to an angular momentum that is independent of the orbital motion. The electron spin is thus identified as a further emergent quantum property, with the correct gyromagnetic factor of 2 for its magnetic moment.

The ergodic properties of the stationary mechanical system—one of the many features that are concealed in usual quantum theory—turn out to be of primary significance, as revealed in Chap. 5. Linked to them is the linear resonant response of the mechanical system to selected modes of the radiation field, encoded in the Heisenberg formulation of quantum mechanics. These are the modes involved in atomic transitions; they are *selected* by the mechanical system, as expressed in the well-known selection rules for atomic transitions. Such rules are here endowed with a physical mechanism (absent in QM) that explains the notorious quantum jumps. According to the results in Chap. 5, for a given state of the atomic electron there is a defined set of resonance frequencies to which it may respond. Which will be the one selected in each instance is a matter of chance, but there is no 'guessing' on the part of the electron about the frequency once the resonance is established. Of course, 'chance' should be here understood to mean that the result depends on a multitude of (unknown and uncontrollable) factors, such as the instantaneous state of the atom and the specific realization of the active mode of the random vacuum field, of which we have neither control nor knowledge.

Further, under certain conditions the ZPF modes have the capacity to induce nonclassical correlations between the parties of a multipartite system, impressing on the latter an effective nonlocal behaviour, encoded in the ensuing entanglement. This observation helps to demystify the mechanism of entanglement by eliminating the spooky nonlocality that seems to characterize it, say, in the case of (classically) noninteracting particles. It is the absence of the ZPF from the usual quantum description what makes of entanglement, and all its peculiar properties, an abstruse feature, difficult to reconcile with the rest of physics. Particularly interesting is the fact that the entanglement of the spin variables in a system of identical particles introduces the demand of antisymmetric wave functions.

The usual quantum-mechanical formalism is known to provide a very accurate description of the time-reversible regime. But strictly speaking, as shown here, it provides only an approximate description for at least two reasons: firstly, the initial transient phase, when field and particle have just started to interact, is not considered; secondly, the radiative terms that were essential in taking the system to the stationary regime, have been dropped from the equations in the derivations leading to quantum mechanics, by taking the radiationless approximation. The first remark should not be a cause for concern (yet), as the initial relaxation time is estimated to be of the order of or shorter than 10^{-20} s. The second limitation is normally lifted by using QED to calculate, perturbatively, the corrections produced by the neglected radiative terms. In SED, by contrast, advantage is taken of the fact that these radiative terms are embedded in the original formulation, as shown in Chap. 6.

Moreover, as follows from Chap. 4, the fact that the initial continuity equation for the phase-space probability density is reduced to an equation in configuration space for the local averaged dynamical variables, indicates that the ensuing (quantum) description is incomplete, this incompleteness being due not solely to its statistical nature, but also to the partial information it bears about the dynamics of the system. Quantum mechanics provides the maximum possible information through the statistical description of (an ensemble of) systems in a certain (radiationless) state. The lost information about the system cannot be reconstructed by going in reverse order, from the reduced x- or p-(or any other equivalent-) representation back to the full phase-space description. An immediate consequence of this is that characteristic quantum features—such as the existence of *irreducible* fluctuations (as encoded in the Heisenberg inequalities), the inexistence of joint probabilities for noncommuting operators, the negative probabilities,[2] the apparent nonlocalities, the nonclassical correlations due to entanglement, and so on—become difficult (if not impossible) to understand from within QM. The physical mechanisms that account for the quantumness are *irreversibly* concealed when the ZPF, the main culprit, has been left out of the picture.

From the present analysis we conclude that even if the description of Nature afforded by present-day quantum mechanics is nonlocal, indeterministic, in some instances noncausal,[3] and free of trajectories and physical images, it strictly speaking does not negate either physical or philosophical realism. It is when one assigns the characteristics of the (partial, asymptotic and approximate) quantum description

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[2] We have in mind true probabilities. Negative 'probabilities' are consubstantial to the technique of the so-called weak measurements, i.e., non-projective measurements (Aharonov et al. 1988).

[3] There are other cases in theoretical physics where approximations transform an otherwise causal theory into one that violates causality. Perhaps one of the best known examples is the Abraham-Lorentz equation of motion. This equation is derived from a perfectly causal combination of Maxwell's theory and classical mechanics. The end result, the Abraham-Lorentz equation, can however give rise to noncausal phenomena as preacceleration, the anticipated response to a future force [see e.g. Eq. (4.42)]. Again in this case, the root of such noncausal behavior is to be found in the approximations leading from the original causal full description to the final simplified (and noncausal) one. Approximate physical theories are not bound to satisfy the same rigorous requirements that fundamental theories are supposed to fulfil; this is particularly true in what refers to consistency with first principles.

to Nature itself, by assuming one or another of the (free) interpretative hypotheses of present-day QM, that realism seems to stall. Reality is richer than that: both QM and realism are alive, each one in its own province. Arguments as those that follow from the present theory show that the frequently repeated dicta about quantum noncausality, essential indeterminism, (irreducible) quantum fluctuations, (unexplained) nonlocality, and the like, normally attributed to Nature, are indeed an attribute of the description. The most essential properties of the classical world maintain their force at the quantum level, although a very specific not-less-powerful-statistical quantum lawfulness emerges from the complexity of the situation.

10.1.1 Origin of Quantization

The fact that from an essentially stochastic theory in which dynamical variables can acquire any value from among a continuum we arrived at a description in which such variables may attain sure, i.e., nonstochastic, and discrete values, seems to be a contradiction, or at least an obscure property. However, there is an explanation for it, and a multifaceted one indeed. The more fundamental reason for the appearance of sharp values for some dynamical variables (in particular the energy) is the highly peaked resonant response of the mechanical system to certain field modes, when energy balance and ergodicity are in place; this leads to a (radiationless) description in terms of eigenvalues of Hilbert-space operators, corresponding to stable stationary motions. Moreover, the quantum description leaves aside small fluctuations around the corresponding eigenvalues (as explained in Chap. 5), which thus appear as nonfluctuating quantities. In other words, Nature is noisier than what the theoretical description (in the quantum-mechanical, radiationless approximation) asserts.

By fixing the reduced set of stationary solutions that are robust with respect to the fluctuations of the field and correspond to a local extremum (minimum) of the mean energy, which makes them particularly stable as discussed in Chap. 4, the resulting ergodicity can be considered the source of quantization in the present theory. At the same time, it becomes intuitively clear that the demand of detailed energy balance can be satisfied only by a selected (frequently discrete) set of motions. By its physical content, the present explanation of quantization stands in sharp contrast to the usual one related to the mathematical properties of the wave function—although they are both *formally* equivalent, as seen in Chaps. 4 and 5. This issue acquires relevance if the wave function is taken as a mathematical object, because even as such it must satisfy conditions of continuity and single-valuedness. In fact these conditions on ψ arise from physical demands (such as that of energy balance in the mean) and, very importantly, from those imposed on the spatial distribution, the flux currents, and so on. This stresses the importance of the fact that the theory leads naturally to the Born rule, which assigns to the wave function its probabilistic meaning and related properties.

10.1.2 Recovering Realistic Images

As discussed in Chap. 8, the notion of trajectory is foreign to QM. This correct conclusion, however, is frequently translated to mean that in the real quantum systems of Nature trajectories do not exist. This would force us to renounce the possibility of constructing a realist image of what a quantum corpuscle is actually doing in space and time, a ban that goes contrary to the precepts and results of the theory here developed.

Since the origins of quantum mechanics, particularly through the foundational work of Heisenberg (see e.g. Jammer 1966), the statement about the inexistence of quantum trajectories has permeated almost every textbook on the subject. The argument is founded on the Heisenberg inequalities, interpreted as saying that non-commuting observables (e.g., position and momentum) imply not simultaneously existing values. However, according to our exposition in previous chapters, the Heisenberg inequalities express an acquired property of the statistical description—ultimately originating in the fluctuations impressed on the particle by the ZPF—once the system reaches the time-asymptotic quantum regime. In other words, they set a limit to the applicability of present-day theory, not an (ontic or epistemic) final limit to our capability of apprehension of Nature, nor to the capacity of a single corpuscle to follow a given (yet unknown) trajectory. Even if the individual trajectories become unrecoverable from the quantum-mechanical description, they exist in nature; they are in fact present in the very initial description in terms of Eq. (4.2), say, but disappear from the narrative in the quantum description as a result of its (reduced) statistical nature. The absence of trajectories in the quantum description is an obstacle of significance for the account of individual events, such as the deflection of single particles by a potential barrier or by the atoms of a crystal, and more importantly, for the construction of a realistic image of the microscopic world.

Among the attempts to introduce hidden variables into quantum theory to recover the hidden trajectories, the best known one is Bohm's causal theory. According to the view here advocated such attempts can have at most a partial success, since the individual behavior of a particle becomes irretrievable once its stochastic motion has been smoothed out by the local averaging process. The only sensible way to follow the real trajectories would be to go back to the original equation of motion (4.2), but even then there is the intrinsic problem of any stochastic description, namely the specific realization of the field is unknown and with it also the specific particle trajectory. The best and only thing one can do in any real situation is, therefore, to resort to the statistical treatment of the problem.

In summary, this means that to the extent that the present theory is a sensible one, the mere addition of hidden variables to the usual (reduced) quantum mechanical description to recover determinism or realism is a very limited recourse. Even if one completes the (quantized) theory by adding the (quantized) background field, as is done in QED, the trajectory of a specific particle remains unknown. In other words, within present-day knowledge an indeterministic *description* of the quantum system results unavoidable. It is interesting to compare this conclusion with the old eagerness, expressed so many times by Einstein as his most tenacious devotee, for a final description free of statistical elements. Unfortunately (for some), that is a goal that seems difficult to attain.

10.2 Some Answers

In the following we list a number of conclusions that can be drawn from the developments, discussions and results presented in the body of this book. The list is intended to address some of the main (physical and conceptual) difficulties associated with the usual interpretations of quantum mechanics mentioned in Chap. 1, and to provide a succinct picture of the way out of such difficulties as offered by present SED. Those readers who have accompanied us throughout this long journey, will appreciate that the assertions made emanate from the theory here advanced and do not ensue from personal preconceptions or prejudices. The list contains what we consider are the most relevant points, but of course it is by no means exhaustive.

- The quantum phenomenon is not intrinsic, neither to matter nor to the field, but emerges from a complex process of matter-field interaction.
- The stochastic zero-point radiation field is the physical entity ultimately responsible for such emergency.
- This applies in particular to the description of the thermal equilibrium radiation field. No assumption of discreteness is required to arrive at the Planck distribution.
- The equilibrium eventually attained by matter and field is such that a (detailed) balance exists between mean absorbed and radiated power at each frequency of the background field. Radiative effects can then be neglected.
- In such time-reversible regime, the mechanical system satisfies ergodic properties. Taken together, detailed energy balance and ergodicity define the *quantum regime*.
- Once in this regime, the evolution of the mechanical system is governed by the quantum laws, in the formulations of Schrödinger and Heisenberg. Both formulations are formally equivalent, yet they disclose different and complementary aspects of the quantum machinery.
- The Schrödinger equation provides a reduced statistical description of an ensemble of particles immersed in a stochastic environment. It is unable to afford in general a detailed account of a single element of the ensemble.
- The Schrödinger equation contains the core of the stochastic source in the form of Planck's constant, which is a measure of the fluctuations impressed by the ZPF.
- The spectral energy density of the ZPF, proportional to ω^3—and hence consistent with special relativity and with the principle of inertia—is essential in ensuring the stability of the ground state. This singles out the ZPF as the physical field responsible for atomic stability.
- The relatively high coherence of the modes of the ZPF that sustain the stationary solutions contrasts markedly with an uncorrelated noise, such as that leading to a single asymptotic (Brownian) solution with purely stochastic motion.

- The transitions between 'stationary' states (hence the states themselves) are determined by the extremely sharp resonances of the mechanical system to the background field.
- The operators and vectors in a Hilbert space are a powerful tool for the statistical description in terms of possible states of the system—though they conceal the physical mechanism sustaining such states, and give no idea of what is happening in real three-dimensional space.
- In a given quantum state, the dynamical variables are controlled by certain modes of the ZPF. The noncommuting operators and the canonical quantum commutator $[\hat{x}, \hat{p}]$ are an imprint of this field.
- The Heisenberg inequalities refer to the minimum statistical variances of the variables, induced by the action of the ZPF. The quantum fluctuations are causal fluctuations due to the (random) field.
- The particles remain particles all the time and follow definite and causal (stochastic) trajectories, but the description of these is beyond the possibilities of the limited statistical treatment offered by quantum mechanics.
- The reduction of the complete statistical description from phase space to the configuration subspace is the source of several of the most characteristic and deceitful properties of the quantum systems.
- In particular, such reduction precludes the possibility to start from QM and arrive, by purely logical steps, at a genuine (Kolmogorovian) phase-space distribution. Such distribution exists, but is beyond the realm of QM.
- The local averaging process conceals the detailed dynamics in phase space and leads to apparent nonlocalities. Therefore nonlocality exists, in the restricted sense that it a feature of the quantum *description*, but it does not refer to an ontological property of Nature. The reduction process leads to the artful transformation of the original local description into a nonlocal one.
- In particular, the concealed momentum fluctuations reappear in configuration space in the form of a strange contribution, conventionaly taken as an additional (quantum) potential, despite its kinetic origin. This 'potential' is an entry point of nonlocality and irreducible fluctuations in the quantum description.
- The resonant response to selected field modes explains the emergence of nonclassical correlations between noninteracting particles. Partners that share common relevant frequencies become entangled, and the high spatial coherence of the field modes involved gives stability to the ensuing states.
- For identical particles subject to the same potential, the entanglement induced by the ZPF common modes is maximal and leads to the (anti)symmetry of the wave function. The antisymmetry of the total electron wave function is rooted in the entanglement of the spin states.
- There are no spooky actions at a distance. It is the ZPF what connects the parties and transforms the bipartite system into a single entity .
- The electron spin is an acquired property that ultimately emerges from the (rotational) fluctuations impressed on the particle by the ZPF. Its magnitude is hidden in the fundamental quantum commutator (the signature of the ZPF).

- Associated with the spin (unavoidable, thus in a sense intrinsic) angular momentum is a gyromagnetic g-factor of value 2, derived from the two degrees of freedom of the circular polarization of the ZPF.
- A moving quantum corpuscle has a physical (de Broglie) wave associated to it. The de Broglie wave possesses an electromagnetic origin, linked with the ZPF. Yet both entities keep their individual corpuscle and wavelike natures, respectively.
- The diffraction pattern formed by a beam of electrons sent through an array of slits reflects the action on them by the diffracted ZPF. The trajectories of individual particles convey and reproduce statistically the wave nature of the diffracted background field.
- The theory defined by the starting Eq. (4.2) derives from a fundamental description that has all the properties that a fundamental realist and objective physical theory should possess: it is causal, deterministic and local. It accepts depictive images and offers a space-time description, without the need to bring the observer into the picture.
- The loss, total or partial, of any of the above mentioned traits, is a result of the approximations, reductions and simplifications made in arriving at the ultimate quantum description. Of particular relevance is the disappearance of the zero-point field from the picture.

10.3 The Photon

The photon is the quantum of electromagnetic interactions. This commonplace statement refers to the photon in interaction with matter—not to the photon itself. If we try to find an answer to the simple question “What is a photon itself?” things become blurred. This is fittingly reflected in the well-known confession by Einstein (1951) to a life-long friend:

> All these fifty years of conscious brooding have brought me not closer to the answer to the question, ‘What are light quanta?’ Of course today every Tom, Dick and Harry thinks he knows the answer, but he is deluding himself.

This popular sentence, written more than sixty years ago, is still very much alive. As a token of this, we recall the discussion organized in 2003 by The Optical Society (OSA) “to bring together different views regarding a question asked over the course of centuries: ‘What is the nature of light?’” The editors of the meeting materials (C. Roychoudhuri and R. Roy) write in response: “Despite significant progress in our understanding, it remains an open question”, and with a similar bent A. Zajonc, one of the contributors to the issue, declares “We are today in the same state of ‘learned ignorance’ with respect to light as was Einstein.”[4]

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[4] The contributions to the cited supplement to Optics & Photonic News are collected in Roychoudhuri and Roy (2003). The book Roychoudhuri et al. (2008) and the proceedings of subsequent SPIE meetings under the same title "The Nature of Light: What are Photons?"contains an ample collection of papers on the nature of the photon, showing the broad diversity of views and deep contradictions still existing on this matter.

The theory developed in Chap. 3 suggests a view of the quantized radiation field that is closer to Planck's than to Einstein's, in the sense that the quantization of the energy of each mode of the radiation field ensues as a consequence of matter-field interaction, the field alone remaining continuous. This contrasts with the intrinsic discrete structure of the radiation field, which is the reading that evolved into the notion of photon (Kuhn 1978)—yet quantum field theory has generally adopted and extended the heuristic point of view proposed by Einstein (1905). We recall that Eq. (3.84)

$$\langle f(\mathcal{E})\rangle = \underbrace{\int_0^\infty W_g(\mathcal{E}) f(\mathcal{E}) d\mathcal{E}}_{\text{continuous}} = \underbrace{\frac{1}{Z_g}\sum_{n=0}^{\infty} f(\mathcal{E}_n) e^{-\beta\mathcal{E}_n}}_{\text{discrete}} \tag{10.1}$$

for the mean equilibrium value of a function $f(\mathcal{E})$ was derived without any quantum assumption, but can be read both in terms of a continuous energy distribution or a discrete set of energy eigenstates. It is also true that such energy eigenvalues are never captured *exactly* in the lab, due to the unavoidable fluctuations (line breadth, and so on), which tend to give a more continuous structure to the energy distribution.

It seems interesting to make a short review of the most usual 'definitions' of the photon. This is a complex task, given their diversity, so we restrict ourselves to some representative examples. Probably the most extended one is precisely the early concept proposed by Einstein himself in (1909) of the photon as a "singular point just like the occurrence of electrostatic fields according to the electron theory", i.e., a singularity surrounded by the electromagnetic field of light of Maxwell's theory. The present-day QED definition of the photon as the unit of excitation associated with a quantized mode of the radiation field (a state of Fock space) does not throw much light on the structure of such quantum, normally understood—or wanted to be understood—as a localized 'particle', but described as an infinitely extended entity. Again, this goes somewhat beyond wave-particle duality, since the definition includes momentum, energy and polarization, but eludes position and time. As Zajonc (2003) puts it "Location in space and in time is no longer a means for theoretically distinguishing photons as elementary particles". Indeed it is well known, since the work of Newton and Wigner (1949), that there is no Hermitian operator that befittingly corresponds to position for photons.[5,6] As Bohm (1951) puts it in an introductory

[5] Newton and Wigner showed that it is not possible to define any position operator for a massless free particle with a nonzero spin, in sharp contrast to the case of massive particles, which can be localized. This is clearly in contradiction to the almost familiar notion of 'position of a photon', as one basic ingredient of the intended theoretical description.

[6] Einstein's photon of (1909) is defined by $E = cp = \hbar\omega$. It was in 1916 that he added a well-defined direction to the photon, transforming it into a 'needle of radiation'. On the other hand, Wigner's
(Footnote 6 continued)
photon is its helicity, which is a Lorentz-invariant concept coming from a subgroup of the Lorentz group for massless particles.

account: “There is, strictly speaking, no function that represents the probability of finding a light quantum at a given point. If we choose a region large compared with a wavelength, we obtain approximately $P(x) \sim \left(E^2(x) + H^2(x)\right)/8\pi h\nu(x)$, but if this region is defined too well, $\nu(x)$ has no meaning.”

The single photon is frequently defined not by its intrinsic properties, but by its capabilities, such as its ability to trigger a single photodetection event. There is then no word about the spatial distribution, because the photon becomes defined by the entire excited optical system, which may be a closed or an open one. For the closed system a single standing-wave mode happens to be enough, whereas in the open case a traveling wavepacket is required. In either case the same energy of one quantum of light, $\hbar\omega$, is considered distributed over the entire apparatus, without a hint as to the localization of the photon. Despite this and other similar obscurities, it is usually asserted that both wave and particle properties are present in the quantum description, considering that the corpuscle aspect is fully described by the language of particle creation and annihilation. The definition reduces then to a description of the mathematics: we are invited to conceive the photon as a discrete excitation of a mode or a set of modes $\{k\}$ of the electromagnetic field in some cavity (see e.g. Muthukrishan et al. 2008). Going to the extreme along this direction of defining the photon by its capabilities, we find the jocund pragmatic definition by Glauber “A photon is what a photodetector detects.” And in the most instrumentalist vein Muthukrishan et al. (2008) add “A photon is where the photodetector detects it.”, whatever the size of the detector. Thus the photon extends in the literature from at least the size of the interferometer to that of an atom, or smaller. It would perhaps be more suitable to say that a photon ends its life where and when the photodetector detects it. On the other hand, one can read here and there of the photon as if it were already well established and experimentally confirmed that it is something like a minuscule localized object with well-defined frequency and wavelength (however, see e.g. Raymer and Srinivasan 2012). We find nevertheless that the photon of QED continues to be something radically different from a localized dimensionless corpuscle, quite far from the initial image conceived by Einstein that comes frequently to the physicist’s mind; indeed, not a more or less localized entity, but something that may be distributed over the interferometer or the resonant cavity.

However, what we find common to all descriptions of the photon is the coexistence of two key elements: (a) the photon is an individualized structure, integral part of an electromagnetic field, and (b) it is capable of *transferring* a mean energy $\hbar\omega$ (from a stationary single mode or from a traveling wave-packet). It can be identified as an independent excitation of the electromagnetic field. This coincides with the image that emerges from the theory developed in Chap. 3; thus, the expression (3.71) for the fluctuations contains both a particulate and a continuous element.[7] As discussed

[7] The *coexistence* of both aspects in quantum behavior has meanwhile become an experimentally verified fact; see Aldemade et al. (1966), Kattke and Ziel (1970). For more recent work on
(Footnote 7 continued)
complementarity see e.g. Jaeger et al. (1995), Englert (1996), Engert and Bergou (2000), Liu et al. (2009) and Flores and de Tata (2010).

earlier, the latter is immediately understood as a manifestation of the Maxwell field. The former, ascribed by Einstein to a *spatial* discreteness of the field, expresses the effects of the zero-point field, according to what we have learned in Chap. 3. Thus the photon is more than a classical Maxwell wave plus the active ZPF: it appears as a packet of the radiation field resulting from its interaction with matter. The field continues to be a field all the time, even if it gains some organization.

As a quantum of the radiation field, the photon appears in the theory, particularly in QED, only interacting (locally) with matter. Indeed, QED is used to describe the mutual effects of matter and field in interaction; this is the standing point from which the present-day notion of photon acquires sense. This standpoint is extended to the free field, assuming that also it requires quantization. However, the free field is an unobserved entity, with properties that are in principle beyond our reach. We have no more ground to assume that the free field *is* quantized, than the heuristic proposal of Einstein for mathematical continuity and physical simplicity of the description. We must be aware that this is an unverifiable extrapolation.

In the present SED account, further to the appearance of the quantized energy of the field in thermal equilibrium with matter (Chap. 3), little contact has been made with the photon. One exception (that addresses the issue only indirectly) is the analysis of radiative corrections presented in Chap. 6, leading to the well-known formulas for the Einstein A and B coefficients for the atomic lifetimes. These formulas clearly imply emission or absorption of a well-defined quantum of energy. In connection with this, we must recall the fact (already discussed above) that in the ergodic regime the atom responds resonantly to field modes of definite frequencies given precisely by the formula $\hbar\omega = \Delta\mathcal{E}$ connecting the energy levels. Therefore, the quantum of photonic energy exchanged between atom and field is in the picture—in relation with radiative processes occurring in matter. An extended SED theory that looks at the entire field-matter system, instead of focusing just on its material part as was done here, should help clarify the nature of the photon.

10.4 Limitations and Extensions of the Theory

To extend the scope of the theory presented in this book, several of the simplifications, reductions and approximations made along its development should be avoided or superseded. An immediate one is our use of a one-dimensional Fourier expansion of the ZPF in both Chaps. 4 and 5, instead of the four-dimensional Fourier expansion proper of QED. This implied averaging over the directions of the wave vectors $\boldsymbol{k}$ for each frequency ω_k, as well as over the states of polarization of the field (except for the analysis of spin, which demanded a separation of the polarization modes). Such averaging limits the scope of the theory from its very beginning and entails the loss of important information, particularly when attempting to construct a more detailed description of the field, to determine higher order corrections, or even to be able to study regions of space, time or matter subject to extreme conditions, as occur in so many situations envisaged by present day cosmology. Similarly, the entire treatment is nonrelativistic, and the Lorentz force has been restricted to its electric component and considered in the dipole (long-wavelength) approximation. Of major significance is the reduction of the description from the entire phase space to the configuration space of the particle; the theory is, consequently, unable to describe very fast processes, since its validity is restricted to small values of the Fourier variable z in Eq. (4.47), such that $pz \leq 1$.

Although the original equations of motion introduced in Chaps. 4 and 5 govern the evolution of the entire system at any given time, their mathematical complexity forced us to focus attention on the solutions near energy balance, when assumptions about ergodicity and stationarity can be reasonably made. This means that the detailed evolution of both the field and the material system during the transient phase from the initial nonequilibrium situation to the quantum regime has not been analyzed. The Heisenberg inequalities, in particular, hold only once the quantum regime is attained. So for extremely short time intervals they can be violated, and although this possibility seems to be difficult to verify at present, it remains open in principle (an example of such possibility is proposed in Sect. 8.1.1 of *The Dice*).

It seems marvelous that after such miscellany of curtailments and approximations, the resulting description, quantum mechanics, manifests itself so powerful and precise as it is known to be. Clearly, each one of these simplifications makes the ensuing theory to depart from the capabilities of a more complete description—and of QED in particular. This explains why, in making contact with QED, the analysis has been restricted to the lowest significative order of approximation (obtaining results that are in full agreement with those of QED). To overcome the limitations of the present theory one should in principle resort to the full phase-space description of the matter-field system. This should help to solve the known problems with the phase space descriptions, of which the Wigner function is the prototype. Of course, the indeterministic description will persist, but the extended theory would offer a finer and fairer description of Nature.

One virtue of the present treatment is that it can help to open opportunities to explore provinces unknown to all three, QM, QED and SED. This is perhaps its most important contribution. Clearly the present theory may—and should—be generalized in several directions. From among the wide range of possibilities let us mention one that seems to be most attractive.

Since the very early days of SED, the possibility of considering space-time metric fluctuations as responsible for the fundamental stochasticity of the quantum world has been entertained. Two immediate advantages are obvious. One is its universality, since all forms of matter and energy are subject to gravitational interaction. This gives an ecumenical answer to the frequent question in SED about neutral particles. An even more significant advantage of such theory would be that it could integratenaturally aspects of both, quantum theory and general relativity, a most desirable property for a theory that should help pave the road to quantum gravity. If such view of nature—intermediate between our present-day quantum theory and the would-be quantum theory of gravity—may be of any help, is something to be explored.

The observation that the vacuum energy fluctuations should give rise to fluctuations of the metric at small distances, has been considered in different contexts and from various points of view. Already in a work by Einstein (1924) stochastic fluctuations of the metric tensor are enterntained as a possible representation of a real, all-pervading material field. Both the mathematical and the physical side of the fluctuating geometry problem have received some attention over the years. The mathematicians have worked on the construction of different types of statistical geometries and their probabilistic topologies, a subject that is of much interest at present. On their part, de Broglie, Rosen, and Blokhintsev, among others, studied time ago the metric fluctuations as a source of the quantum fluctuations; the results appear scattered in the literature, without having led to an accomplished theory (a list of references up to approximately 1980 is given in Vigier 1982). A renewed interest seems to be flourishing, with different and more actual ideas and viewpoints (we refer for example to Carlton 1976; Namsrai 1986; Petroni and Vigier 1984; Bergia et al. 1989; Bergia 1991; Sorkin 1994; Santos 2006; Giovannini 2008; Gasperini 2011) . The connections between a phenomenological description of the fluctuations of the metric and the stochastic theory of quantum mechanics, among other things, have been explored by Roy (1986, 1992) and more recently in Vasudevan et al. (2008), whereas in their formulation of geometrodynamics, Bergia et al. (1989) have considered a model within the Kaluza-Klein framework. Several related aspects of the subject are currently under study, though with emphasis on the relativistic aspect, rather than its quantum implications. It would be premature to draw definitive conclusions about the merits and possibilities of such work; nevertheless, it is clear that they are worth further efforts.

The most ambitious task for present-day theoretical physics is just the development of a unified theory of the forces of nature. The efforts invested, both human and economic, in the search of such theory have been considerable, and the results for physics still quite limited. The two theories that give support to such efforts are general relativity and quantum mechanics. Present-day quantum theory, with all its conundrums, is being used in the search for a theory that pretends to describe the world as it is supposed to be fifteen or more orders of magnitude apart from our present scale of energies and times. This means transferring to the supposedly fundamental theory the problems and confusions that beset quantum theory today—and with an amplified dose of ignorance. Before taking such bold and unwarranted step it is best to clean the house and disclose the rich physics that remains invisible to the usual quantum description. Here we offer a contribution to this task.

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