The relation between classical and quantum electrodynamics

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Abstract

In this article it is presented the idea that quantum electrodynamics presents intrinsic limitations in the description of physical processes that makes it impossible to recover from it the type of description we have with classical electrodynamics. In this way I cannot consider classical electrodynamics as reducing to quantum electrodynamics and being recovered from it by some sort of limiting procedure. Quantum electrodynamics has to be seen not as an independent theory but just as an upgrade of classical electrodynamics and the theory of relativity, which permits an extension of classical theory in the description of phenomena that, while being clearly related to the conceptual framework of the classical theory – the description of matter, radiation, and their interaction –, cannot be properly addressed from the classical theory.

1. Introduction

In the wonderworld of physics it is usually perceived that the relation between the classical and quantum theory is unproblematic and that under a more or less clear procedure we can regard the classical theory as some sort of limit of the quantum theory. Usually these considerations are done in the realm of non-relativistic quantum theory and not much is said about the relation between quantum electrodynamics and classical electrodynamics. Be it the relativistic or non-relativistic theory, we are in the paradoxical situation, which is usually present as non-paradoxical and natural, that the quantum theory is supposed to contain the classical theory but at the same time needs it to its own fundamentation (Landau, 1974, p. 13). I do not agree with this view.

In the following I will try to present the argumentation that classical electrodynamics and quantum electrodynamics form a not very consistent theoretical structure in which the quantum part has to be seen as an extension of the classical part and not as containing the classical theory. In this way quantum electrodynamics cannot be seen as an independent theory of physics.

In section 2 it is presented the current classical framework provided by classical electrodynamics and the theory of relativity, and it is address the question of the possible inconsistency of classical electrodynamics. In section 3 the development of quantum electrodynamics from the quantization of the classical Maxwell field and the classical Dirac field is considered. The possibility of a classical limit is addressed, and taking into account the limitation of quantum electrodynamics in the temporal description of scattering processes it is considered that properly speaking we cannot reduce classical electrodynamics to quantum electrodynamics.

2. Classical electrodynamics

The classical electromagnetism as used nowadays is not the theory as developed by J. C. Maxwell. In is more mature work, published in 1873, Maxwell used the Lagrangian formalism to avoid any specific mechanical model of the medium that causes the electric and magnetic phenomena (Harman, 1982, p. 118). His approach was centered in the description of this medium – the ether. The electric current was described as a variation of the polarization – seen as a more fundamental concept – in a material medium (dielectric or conductor); and in this line, the electric charge was considered 'simply' as a spatial discontinuity in the polarization (Darrigol, 2003, p. 164). In practice Maxwell considered the ether and matter as a single medium existing in absolute space (Harman, 1982, p. 120), more exactly, he treated matter "as if it were merely a modification of the ether" (Whittaker, 1910, p. 288). This was a macroscopic theory of the electromagnetic medium that did not made a clear cut distinction between matter and ether.

In 1892, what can be considered as a new microscopical classical version of electrodynamics was developed by H. A. Lorentz. Taking the previous view of microscopical charged particles used in action-at-a-distance theories, Lorentz combined it with the Maxwell theory of the ether in a way that enable him to explain Fresnel results about the propagation of light in moving bodies. The positive and negative charged material particles would move in the ether without dragging it and only interacting with each other through the mediation of the ether that filled all space: they have a delayed interaction (Whittaker, 1910, p. 420).

Lorentz presented the foundamental equations of his theory as a generalization of the results provided by electromagnetic experiments (Lorentz, 1909, p. 14). This means that he made and extension of Maxwell macroscopic field equations to a microscopic level taking into account his consideration of the charge as a density distribution attached to a microscopic solid body. With this microscopic and atomistic turn, the field equations are in Lorentz electrodynamics given by: div $\mathbf{d} = \rho$, div $\mathbf{h} = 0$, rot $\mathbf{h} = 1/c\ (\mathbf{d}' + \rho\mathbf{v})$, and rot $\mathbf{d} = -1/c\ \mathbf{h}'$, where $\mathbf{d}$ is the dielectric displacement, $\mathbf{h}$ is the magnetic force, ρ is the charge density, and $\mathbf{v}$ is the microscopic body absolute velocity (Lorentz, 1909, p. 12).

Lorentz considered that the ether pervades all space including the 'interior' of the solid bodies, but being always at rest in relation to the absolute space. The law that dictates the influence of the electromagnetic fields, as a manifestation of the internal state of the ether, on the charged bodies, can be seen, as in the previous cases, as an extension of the experimental results as traduced by the force laws of Coulomb and Biot-Savart, and is given by $\mathbf{f} = \mathbf{d} + 1/c\ [\mathbf{v}\cdot\mathbf{h}]$.

These five equations with their underlying assumptions can be considered the core of Lorentz electrodynamics (McCormmac, 1970).

With Lorenz's electrodynamics the conceptual distinction between matter and ether is clearer than in the Maxwell theory. We have a more precise physical characterization of matter, ether, and their interaction, and the scope of application of the theory is extended. In this way we can consider Lorentz electrodynamics as more fundamental than Maxwell's. But it appears to have a weak spot, which is maintained even after considering A. Einstein contribution to classical electrodynamics with the downfall of the concepts of ether and absolute space and the rethinking of electrodynamics under the more general theory of relativity.

When in his first works on the subject Lorentz considered the existence of charged corpuscles, he associated them with the ions of electrolysis. P. Zeeman experimental results that the charge to mass ratio of the particles was one thousand times smaller than supposed indicated that these particles were not the ions of electrolysis. This conceptual distinction lead Lorentz to consider the existence of sub-atomic corpuscles (with positive or negative charge), adopting as others the term 'electrons' (Arabatzis, 1996, pp. 421-424). Lorentz considered the electron as a charged rigid body, giving to it a "certain degree of substantiality" (Lorentz, 1909, p. 14), to which the laws of motion apply. Lorentz modelled the electron as a sphere with a uniformly distributed surface charge. He considered the electron when in motion in relation to the ether (in repose in absolute space) to take the form of an elongated ellipsoid. Considering a very small departure from uniform motion and applying expressions obtain in that case, Lorentz determined “the force on the electron due to its own electromagnetic field” (Lorentz, 1909, p. 38). He found that this effect corresponded to the existence of a mass of electromagnetic origin and was taken to the idea of an effective mass composed of the mechanical mass and the electromagnetic mass. Due to Kaufmann's experiments, and not considering the mechanical mass from the point of view of the not yet developed theory of relativity but from Newtonian mechanics, Lorentz even considered the possibility that the electron's mass was all of electromagnetic origin. Lorentz work was critically examined by H. Poincaré who concluded that it was needed a non-electromagnetic internal pressure so that the electron was stable under the electrostatic repulsion between its elements of charge (Poincaré, 1905).

From the point of view of the theory of relativity it is clear that the mass of the electron cannot be solely of electromagnetic origin. The electron's momentum and energy originated by its own field do not form a four-vector. In relativistic mechanics we can consider a particle to be defined by having a determined energy-momentum four-vector (Jammer, 1961, p.164). This definition can be justified without taking into consideration any aspect of electrodynamics, as G. N. Lewis and R. C. Tolman have done: we can determine the relativistic expression for the particle's mass by considering the collision between the particles and postulating a conservation law of momentum and using the relativistic law of addition of velocities (Pauli, 1958, p. 118). From this it is immediate to see that the momentum and the energy of the particle behave under Lorentz transformation as the components of a four-vector. This result can be checked experimentally again without any explicit use of electrodynamics, as has been done in the early thirties by F. C. Champion, who studied the scattering of β-particles with electrons at rest in a Wilson chamber (Zhang, 1997, p. 234). This means that the experimental and conceptual framework of relativistic mechanics can be developed and verified on its own, disattached from any electrodynamics considerations. This point is crucial in the analysis of results obtained with different models of the electron.

When considering a point-like model of the electron, the self-energy is infinite. In 1938, P. Dirac proposed a clear covariant procedure to separate the finite and infinite contributions to the self-energy (Dirac, 1938). The infinite contribution to the electron's mass is taking care off by a renormalization procedure in which the observed mass encloses the mechanical mass and the (infinite) electromagnetic mass. The finite effect is a reaction force depending on the derivative of the acceleration. So, when considering the electron's self-energy we have a departure from the Lorentz force equation and obtain an equation – the Lorentz-Dirac equation – in which besides the external force we have present the radiation reaction from the electron's field. This equation has very unphysical solutions. In the absence of any external force the equation admits solutions where the radiation reaction provides a self-acceleration to the charged particle. Choosing appropriate asymptotic conditions this type of solution is avoidable. Nevertheless a problem still remains. When considering the case of a particle subject to an external force, the motion of the particle is affected by the force even “before the action of the force” (Barut, 1964, p. 198): we have a pre-acceleration of the electron before the action of the external force. It seems that the point-like electron is not a classically acceptable model. The pre-acceleration solution, where we have a non-zero acceleration before the external force is applied, appears to be avoidable with a classical extended electron model. Let us consider a model of the electron consisting in "a charge *e* uniformly distributed on the surface of an insulator which remains spherical with constant radius *a* in its proper inertial frame of reference" (Yaghjian, 1992, p. 31). Taking into account the finite velocity of propagation of an electromagnetic disturbance across the 'electron', in the mathematical determination of the solution to the equation of motion of this 'electron' no pre-acceleration solutions occurs. This result has been challenged, and it might be the case that even this model does not resolve the problem of pre-acceleration (Frisch, 2005, p. 62). In this way there seems to be no conceptually unproblematic way to overcome the inconsistency of applying Lorentz laws of electrodynamics taking into account energy-momentum conservation when considering a particle-field system where the self-field of the particle are ignored. In this way it appears that "the standard way of modelling phenomena involving the interaction between discrete charged particles and electromagnetic fields relies on inconsistent assumptions" (Frisch, 2007, p. 2). I think that more than some sort of inconsistency we are facing here interesting and revealing aspects of classical electrodynamics. I think one thing that we can conclude from the analysis that led to the inconsistency claim, is that we have a limited description of matter within classical theory. As it as been noted regarding classical electrodynamics, "the main problem with taking this theory to be the fundamental theory of the interaction of classical charges and fields is that it is in an important sense incomplete. Without substantive additional assumptions concerning how charged particles are to be modelled, the theory cannot be understood as describing the behaviour of the particle-field system" (Frisch, 2005, p. 47). Basically we only have general rules from relativistic mechanics that give an overall prescription about what general laws must matter 'obey', like the definition of the concept of particle by considering that it must have a certain energy-momentum four-vector, which is independent of any particular model of the particle and the possible inconsistency of any derived force law. We really do not have any elaborated theory of matter. From this I would say that the classical theory is incomplete, in the sense that part of its conceptual framework – the one related with the description of matter – shows severe limitations. It is difficult to consider (in some way) inconsistent something that we know it is not complete.

Another aspect, related to the previous, is that the theory was design by considering two clearly distinct entities: the field and the particles, and in the usual applications of the theory "electric charges are treated *either* as being affected by fields *or* as sources of fields, but not both" (Frisch, 2004, p. 529). In trying to overcome this approximative approach the development of the theory faces clear difficulties that within the classical approach seems to have no easy solution. In this way considering also the case of quantum electrodynamics (Bacelar Valente 2008a) it seems that we might be facing the intrinsically approximative character of the description of the interaction of radiation and matter, that seems inevitable in the present approach followed in physics developed by considering radiation and matter as two clearly distinct phenomena. If it turns out to be so, we are really facing more than 'simply' a problem of incompleteness of the classical theory.

3. Quantum electrodynamics and the so-called classical limit

Within quantum electrodynamics (or more generally quantum field theories) the starting point are classical fields like the Maxwell field and the Dirac spinor field defined on a Minkowski space-time. We can see the quantization scheme as a set of physical rules that enable an extension of the applicability of the classical concepts to phenomena that while being ‘categorized’ as related to matter, radiation and their interaction, are beyond the classical sphere of description.

Considering the usual quantization procedure, in the case of a free Maxwell field the vector potential can be expanded as

$$A^{\mu}(x) = \sum_{r\mathbf{k}} \left(\hbar c^2 / 2V\omega_{\mathbf{k}} \right)^{1/2} \left(\varepsilon_r^{\mu}(\mathbf{k}) a_r(\mathbf{k}) e^{-ikx} + \varepsilon_r^{\mu}(\mathbf{k}) a_r^{\dagger}(\mathbf{k}) e^{ikx} \right)$$ (Mandl & Shaw, 1984, p. 84).

In order that $A^{\mu}(x)$ can be related to the Maxwell equations a subsidiary condition is imposed, the so-called Lorentz subsidiary condition, which at a quantum level has to be changed (Bogoliubov & Shirkov, 1959, pp. 56-57).

In this case the connection between the classical equations and concepts and their quantum upgrades are very direct. Under the quantization scheme $A^{\mu}(x)$ is now a field operator, and the Fourier expansion coefficients are now, as operators, conditioned by the commutation relations $[A^{\mu}(x), A^{\nu}(x')] = 0$, $[A'^{\mu}(x), A'^{\nu}(x')] = 0$, and $[A^{\mu}(x), A'^{\nu}(x')] = -i\hbar c^2 g^{\mu\nu} (\mathbf{x} - \mathbf{x}')$ (Mandl & Shaw, 1984, p. 86).

In the case of the Dirac equation, it might seem that the situation is not so simple. But it really depends on how we chose to look at the equation. Considering Dirac's equation as a classical equation of an electron-wave, that can have its properties explored in experiments like the diffraction experiment of Davisson and Germer (Tomonaga, 1962, p. 10, Vol. 2), following P. Jordan, we can consider the quantization of this classical spinor field, using in this case anti-commutation relations, and obtaining, by a procedure even more simple than the quantization of Maxwell field, the Dirac field operators

$$\psi(x) = \sum_{r\mathbf{p}} (mc^2/VE_{\mathbf{p}})^{1/2} \left(c_r(\mathbf{p}) u_r(\mathbf{p}) e^{-ipx/\hbar} + d_r^*(\mathbf{p}) v_r(\mathbf{p}) e^{ipx/\hbar} \right),$$

$$\overline{\psi}(x) = \sum_{r\mathbf{p}} (mc^2/VE_{\mathbf{p}})^{1/2} \left(d_r(\mathbf{p}) \overline{v}_r(\mathbf{p}) e^{-ipx/\hbar} + c_r^*(\mathbf{p}) \overline{u}_r(\mathbf{p}) e^{ipx/\hbar} \right),$$

where c_r^*, d_r^*, c_r and d_r obey the anti-commutation relations $[c_r(\mathbf{p}), c_r^*(\mathbf{p})] = [d_r(\mathbf{p}), d_r^*(\mathbf{p})] = \delta_{rs}\, \delta_{\mathbf{pp}'}$, with all other anti-commutation relations vanishing (Mandl & Shaw, 1984, p. 68).

We can see Dirac's equation as a classical level description of matter from a wave perspective, but in agreement with the laws of relativistic mechanics (Bacelar Valente 2008a). In particular the relativistic Hamiltonian $H = c(m^2c^2 + p_1^2 + p_2^2 + p_3^2)^{1/2}$ can be seen as fundamental in the derivation of Dirac's equation (Dirac, 1958, p. 255). Dirac considered that the relativistic wave equation of the electron should be linear in $p_0 = i\hbar\, \partial/(c\partial t)$ and $p_r = -i\hbar\, \partial/(c\partial x_r)$ with $r = 1, 2, 3$. In this way it had the form $(p_0 + \alpha_1 p_1 + \alpha_2 p_2 + \alpha_3 p_3 + \beta)\psi = 0$. The matrices α_1, α_2, α_3 and β, are determined by the relativistically invariant equation $(p_0^2 - m^2c^2 - p_1^2 - p_2^2 - p_3^2)\, \psi = 0$ defined using the relativistic Hamiltonian (Dirac, 1928).

Also the spin of the electron, usually presented as a quantum concept related with a particle view of the electron without any classical counterpart, can be seen as related to the wave aspect of the description of the electron. Considering the classical Dirac wave symmetrical energy-momentum tensor

$$T_{\mu\nu} = \frac{hc}{4i}\left\{ \psi^{\dagger}\gamma^{\mu}\frac{\partial \psi}{\partial x_{\nu}} + \psi^{\dagger}\gamma^{\nu}\frac{\partial \psi}{\partial x_{\mu}} - \frac{\partial \psi^{\dagger}}{\partial x_{\nu}}\gamma^{\mu}\psi - \frac{\partial \psi^{\dagger}}{\partial x_{\mu}}\gamma^{\nu}\psi \right\} ,$$

the momentum density is given by $\mathbf{G}_k = \mathbf{T}_{4k} / ic$, and from it the angular momentum of the wave (or quantum field after quantization) $M = \int dx\, x\mathbf{G}$ is derived. Separating the angular momentum in two terms we have $M = M^0 + M'$, with

$$M^0 = \frac{h}{2i}\int_V dx x\{\psi^* \nabla \psi - \nabla \psi^* \psi\}$$

and $$M' = \frac{h}{2}\int_V dx \psi^* \sigma \psi .$$

After the quantization M' is the spin angular momentum operator (Wentzel, 1942, p. 182). This simple derivation shows clearly that the spin comes out of a Dirac field without any need to consider any particle-like properties (Ohanian, 1985).

One relevant aspect related to spin is that its comprehension is achieved by analysing in classical terms the results of experiments like the Stern-Gerlach experiment. In this experiment a beam of neutral atoms that is prepared in a determined state passes in a region with an (classical) inhomogeneous magnetic field. The field produce by the apparatus provokes a force in each of the atoms that, due to the quantization of the electron spin, are deflected and cluster around two spots of the detecting screen (Bohm, 1951, p. 326). The theoretical comprehension of the spin emerges from the classical electrodynamics description of the Stern-Gerlach measurement apparatus. This takes me to the Bohrian idea of the need of classical physics to interpret the results of experiments related with the application of the quantum formalism (Howard, 1994). We will need in some point to consider an 'Heisenberg cut' that separates the quantum level of description of a system (obtained by a quantization procedure) from the description of the experimental setup at a classical level, which permits the description of the quantum system interacting with a classically described measurement apparatus (Landsman, 2006, p. 16). This makes possible the interpretation of the quantum formalism in terms of probabilities for experimental outcomes for an ensemble of equally prepared systems that are subjected to the same experimental setup (Falkenburg, 2007, pp. 205-207).

It is usually considered that classicality emerges from quantum theory. In this way it would be possible "the recovery of classical physics from quantum theory" (Landsman, 2006, p. 38), but a definition of a limiting procedure in which classical theory appears as some sort of limit of quantum theory presents mathematical and conceptual problems that have not received an unequivocal answer (Landsman, 2006).

In general the idea of a classical limit is that we might define a sort of mathematical limit that correspond to a "succession of quantum mechanical theories" (Rowe, 1991, p.1111) that would take us from quantum to classical physics. In this way "a explicit algorithm may then be used to construct the classical phase space, define a consistent Poison bracket, and find a classical Hamiltonian, such that the resulting classical dynamics agrees with the limiting form of the original quantum dynamics" (Yaffe, 1982, p. 408). The point is that the 'original' quantum dynamics is constructed by a quantization procedure from the classical description, as was done by Dirac using classical Hamiltonians and the Poisson brackets (Kragh, 1990, p. 19). To develop a sort of mathematical procedure to go the other way around can be seen as a consistency check independently of the possible interpretation of this procedure as an emergency of classicality (Bohm, 1951, p. 626).

To present classical electrodynamics as a classical limit of quantum electrodynamics is a tricky business, but with the usual long mathematical manipulations we might recover from quantum electrodynamics expressions that look like some expressions of classical electrodynamics, and with this have the impression of obtaining a classical limit of quantum electrodynamics (Stehle & DeBaryshe, 1966; Dente, 1975). The point is that in this mathematical jungle we are loosing site of the physical interpretation of the quantum electrodynamics formalism. This is made clear considering the temporal description of physical processes within quantum electrodynamics as compared to the description we have at a classical electrodynamics level.

The retardation due to the finite velocity of propagation of the electromagnetic interaction should be revealed in a quantum electrodynamics treatment by looking at the quantum description of the electromagnetic interaction between electric particles. Within quantum electrodynamics this means principally to consider the description of scattering processes. The problem is that quantum electrodynamics does not provide a temporal description of scattering, it only provides "transition probabilities which correspond to measurable relative frequencies. But it treats the scattering itself as a black box" (Falkenburg, 2007, p. 131). In this way, for example, in the description of electron-electron scattering we do not have access to a description of the electromagnetic interaction as a process occurring in time (Bacelar Valente 2008b & 2008c). We might hope that this is only a consequence of the particular way in which scattering is described, and that in other applications of quantum electrodynamics in the description of interaction processes this situation does not arise. It looks like a simple treatment of the interaction between two atoms might provide just that (Fierz, 1950): when an atom initially in an excited state decays emitting a photon, it will only be absorbed by a second atom (initially in his ground state) after roughly the time r/c (where r is the distance between the atoms).

There is a huge difference between the quantum electrodynamics treatment of a two-atom system and the description of scattering processes. In the model we obtain the desired result by patching together different parts while the S-matrix calculation of scattering amplitudes is a direct application developed from the Lagrangian of interacting Dirac and Maxwell fields. In the model, first we obtain a wave function associated with the electron bound in a atom by solving the Dirac equation as a relativistic one-electron equation, using the equation in a way that it is known not to have a consistent interpretation (Schweber, 1961, p. 99), and then define field operators using these solutions. In this way in the field operators that are associated with the electrons we have contributions that from a quantum field theory point of view are related also to positrons (Bacelar Valente 2008a). These operators are used within the S-matrix formalism which from a mathematical point of view is doable (Jauch & Rohrlich, 1976, pp. 318-319), but which do not corresponds to a full quantum field theory calculation; properly speaking it is a semi-classical calculation due to the used of an unquantized external field (Bacelar Valente 2008a). In any case in the model development it is only made use of very general characteristics of these field operators (Pauli, 1973, p. 133).

To arrive at the pretended result it is fundamental the relation $\omega_0 T \gg 1$ between the time of the emission process T and the energy of the emitted photon ω_0. This relation is a result from the classical theory of the natural line breadth, which can be made plausible in a quantum theory calculation (Heitler, 1954, pp. 181-184), and can be seen simply as following from considering a generalized correspondence principle (Falkenburg, 2007, pp. 188-191). Taking into account this relation and the corresponding emission line, a specific form is given to the bilinear density $\overline{\psi}\gamma^{\mu}\psi$ in the second order term of the S-matrix used in this model. In this way the – classical derivable – spectral line curve is a fundamental aspect of this model (Fierz, 1950, pp. 734-735; Pauli, 1973, pp. 134-135). The final ingredient is an adjustment by hand of the distance between the atoms so that the second atom lies in the wave zone of the first. The point is that in the near zone the photon behaves as a virtual one, while in the wave zone we have (as a limit) the energy-momentum relation for a ‘real’ photon, which means that in the last leg of the model development, depending on how we choose the distance between the atoms, we can have a situation where we can associate a causal temporal order to the emission and absorption process of a ‘real’ photon or a situation where it is not possible to associate a causal temporal order to the emission and absorption of a ‘virtual’ photon.

Another difference between this model and the S-matrix calculations of scattering processes is that in the second case we obtain results that can be compared to experiments (Falkenburg, 2007, pp. 105-107) while in the first case we can only associate with the model a gedanken experiment (Buchholz & Yngvason, 1994, p. 613). In this way the model patched from the theory gives the impression of a solid verifiable consequence that it really is not. In resume, we are using a model that describes a gedanken experiment; it makes reference to general aspects of the electron's wave function that results from using Dirac equation not as a classical wave equation from which a quantum field is derived by a quantization procedure but as a semi-classical one-electron equation (Schweber, 1961, p. 100)[1]; ultimately the main input that determines the form of the bilinear density is not provided by the Dirac equation computation but by a heuristic use of what can be seen as a classical result for the radiation emission of a bound electron and a adjustment by hand of the distance between the atoms to make it possible to obtain the desired temporal behaviour. This does not seem to be a solid procedure we can use to defend that we can regain within quantum electrodynamics the possibility of a temporal description of processes that we have in classical electrodynamics.

[1] Usually the term semi-classical is used when considering some heuristic approach with both classical and quantum components. One example is Møller's original derivation of an electron-electron scattering formula based on the correspondence principle (Kragh, 1992, pp. 310-312), but whose rigorous justification is only possible when deriving it from quantum electrodynamics (Jaynes, 1973, p. 40). In here I am also using the term semi-classical when we seem to have a classical potential in a quantum electrodynamics equation. This situation result from using the so-called external field approximation (Jauch & Rohrlich, 1976, p. 303), where it appear to be a classical potential within the quantum formalism, but that really is due to a quantum field theoretical description of the interaction with a very heavy charged particle (described by a quantum field) when its recoil is neglected (Schweber, 1961, p. 535). It is within the external field approximation that a Dirac field operator equation with an ‘external’ field appears, and from which, the relativistic one-electron equation with a ‘classical’ potential can be seen to emerge from the full quantum electrodynamics (Jauch & Rohrlich, 1976, pp. 307 & 313).

I think we have always to stick to the physical interpretation of quantum theory[2] and consider clear applications of quantum electrodynamics related with doable experiments. In this way from what has been presented I cannot consider that from the quantum level of description it is possible to recover the temporal description of processes that we have at a classical level. Due to this I simply do not consider quantum electrodynamics as an independent theory. I call it a physical-mathematical upgrade of classical theory (electrodynamics and theory of relativity) which permits an extension of the applicability of classical theory in the description of natural phenomena, but to which it is not possible to reduce the classical theory.

Conclusions

Under these circumstances, where there seams to be no smooth non-patchy way to connect quantum electrodynamics with classical electrodynamics, the status of quantum electrodynamics as to be reviewed. Quantum electrodynamics cannot be seen as an independent theory that "contains [classical] electrodynamics as a special case" (Stehle & DeBaryshe, 1966, p. 1135). Quantum electrodynamics as an upgrade of classical electrodynamics (and the theory of relativity) can be seen as part of a more general theoretical structure that is expected to describe with both its classical and quantum parts what we consider to be the phenomena of matter, radiation and their interaction. Quantum electrodynamics works as an extension of the classical theory into 'regions' where this fails completely, but since it has been developed from classical concepts, and its probabilistic interpretation puts clear constraints on the applicability of the theory, and not being possible to recover fully the kind of physical description we have with the classical theory, we cannot expect that we can recover the classical part of the description of the phenomena from the quantum part.

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[2] In this article I am not taking into account different interpretations of quantum theory and different approaches to the quantum theory of measurement. I am solely developing my argument within an ensemble interpretation (Isham, 1995, pp. 80-81) that gives a natural connection between the calculations done using quantum electrodynamics and the results from the experimental procedures followed (Falkenburg, 2007, pp. 106 & 207).

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