Photons and temporality in quantum electrodynamics

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Abstract

The lowest order processes described within quantum electrodynamics are free from the problem with infinities in the theory, and can be dealt with disregarding the need for charge and mass renormalization. This might indicate that the space-time description of these processes is not only consistent but also could give a privileged insight to the functioning of models provided by the theory. The Møller scattering is as R. P. Feynman considered, a prototype for the development of his rules of quantum electrodynamics and his overall space-time approach. The study of Møller scattering might then provide the most straightforward way to the understanding of the space-time description of interactions provide by quantum electrodynamics. This method is much less powerful than might be expected at first, pointing to the intrinsic limitations of the theory in what regards the modelling of the temporality in interaction processes.

1. Introduction

It is well known that during the development of quantum electrodynamics during the 1930s and most of the 1940s, the calculations beyond the lowest order of perturbation theory gave infinite corrections to the results, up until the renormalization program succeeded in "sweeping the dirt under the rug" (Feynman, 1962, p. 137).

P. Dirac, who was not convinced with the success of the renormalized quantum electrodynamics commented that "what we need and shall strive after is a change in the fundamental concepts, analogous to the change in 1925 from Bohr to Heisenberg and Schrödinger, which will sweep away the present difficulties automatically" (quoted in Kragh, 1990, p. 183).

Considering the way the infinities were dealt with in quantum electrodynamics, speculation arose about possible improvements over this situation, taking physicists like S. Tomonaga to consider that "the progress we would have attained is only a transitionary one, and the real solution still lies far ahead. This solution might involve a fundamental change in our concepts of nature, such as the discontinuous structure of time and space, or it might require a radical modification of our concepts of elementary particles and their mutual interaction" (quoted in Aramaki, 1989, p. 94).

It might seem that the lowest order applications of the theory, where there are no infinities to battle with, are free from problems, and that in particular Feynman's space-time approach to quantum electrodynamics might provide a consistent means of representation and visualization of the lowest order processes in quantum electrodynamics. Things are not quite that simple.

In section 2 it considered the derivation of Møller's semi-classical formula for electron-electron scattering by a full quantum electrodynamic treatment using the so-called Feynman's fundamental formula directly related with the second-order term of the S-matrix expansion. It is defended that we do not have to see Feynman's fundamental formula as simply related to part of an infinite power series expansion of the S-matrix and that a model developed from this formula is valuable on its own and we can use it in the exploration of the space-time description of process within quantum electrodynamics. In section 3 the quantum model for the lowest order calculation of the electron-electron scattering that permits the derivation of the Møller formula is used to

analyse the type of description of interaction provided by quantum electrodynamics and its limitations, in particular at the level of a temporal description of the interaction as a process occurring in time. To better understand this intrinsic limitation in relation to the classical description a quantum model for the interaction of two atoms is considered.

2. Møller scattering and Feynman's fundamental equation

In the early 1930s, the relativistic electron-electron scattering was treated using a semi-classical approach in the lowest order of perturbation theory. C. Møller used in Maxwell equations the charge and current densities associated with the state transition of an electron from an initial to a final free state as described by the Dirac equation. The retarded potentials determined in this way interacted with a second electron resulting in a state transition of the electron. With this scheme Møller obtained a symmetrical expression for the matrix elements for the scattering of two electrons interacting via classical retarded potentials (Heitler, 1954, p. 233). Around the years 32-33, the use of correspondence methods by Møller lost part of its appeal, due to Bethe and Fermi's demonstration that the formula could be derived within quantum electrodynamics and Bohr's confidence on the logical consistency of the theory (Kragh, 1992, p. 324), even if in the aftermath due to the divergence problems in the theory, Bohr considered that physics was "confronted with the necessity of still more radical departure from accustomed modes of description of natural phenomena" (quoted in Schweber, 1994, p. 84).

Møller's scattering formula did not attract much attention during the thirties and forties, until it revealed itself as an almost immediate application of the new formulation of quantum electrodynamics (Roqué, 1992, p. 256).

Following J. A. Wheeler view, based on his scattering theory, that all physical phenomena could be seen as scattering processes (Schweber, 1994, p. 379), Feynman considered the mutual interaction of two electrons as a fundamental interaction described by his fundamental equation for quantum electrodynamics (Feynman, 1949b, p. 772). It is true that Feynman made reference to the use of perturbation theory in the determination of corrections to the Møller scattering involving two virtual quanta (a higher-order correction); also in a footnote to one of his articles he related his overall space-time approach to the Heisenberg S-matrix theory (Feynman, 1949b, p. 771). But, his fundamental equation 'shines' almost on its own, much because this is the simplest description of electron-electron interaction – and according to Wheeler-Feynman "any physical problem can be defined in terms of scattering processes" (Feynman, 1949b, p. 771) –, but also because this equation set the example for the Feynman rules and presented Feynman's guessing for the extension of the expression for the amplitude from the case of a Coulomb interaction between particles without spin to the relativistic case of delayed interaction between electrons as described by the Dirac equation (Mehra, 1994, p. 285). The Møller scattering formula is obtained directly from this equation when Pauli exclusion principle is taken into account (Feynman, 1949b, p. 773).

Feynman's approach was given a more formal structure by F. Dyson. Considering the perturbative solution of the Tomonaga-Schwinger equation in terms of a unitary operator, Dyson realized that when taking the limits for an initial state in the infinite past and a final state in the infinite future, Schwinger's unitary operator was identical to the Heisenberg S-matrix. Following Feynman's symmetrical approach between past and

future, Dyson used a chronological operator P() that enabled him to present the S-matrix in the form

$$S(\infty) = \sum_{n=0}^{\infty} (-i/\hbar c)^n [1/n!] \int_{-\infty}^{+\infty} dx_1 \ldots \int_{-\infty}^{+\infty} dx_n P(H^I(x_1), \ldots, H^I(x_n)) \ ,$$

where $H^I(x)$ is the interaction term of the Hamiltonian for the Maxwell and Dirac fields system (Dyson, 1949, p. 492). In the case of the electron-electron scattering, the second-order term of this expansion is related to what Feynman called his fundamental equation.

The S-matrix program was originally developed by W. Heisenberg as an alternative to quantum field theory. His idea was to sidestep the problem of divergences in quantum field theory – in his view due to the point-like interaction between fields – by considering only what he saw as measurable quantities (Miller, 1994, p. 97). Heisenberg's idea was to retain only basic elements of the quantum field theory like the conservation laws, relativistic invariance, unitarity, and others, and to make the S-matrix the central element of a new theory (Pais, 1986, p. 498). This was not done because in practise it was not possible to define an S-matrix without a specific use of the theory it was intended to avoid (Cushing, 1986, p. 118). The S-matrix reappeared now in mainstream physics with Dyson's use of it as a calculational tool. In Dyson's view the "Feynman theory will provide a complete fulfilment of Heisenberg's S-matrix program. The Feynman theory is essentially nothing more than a method of calculating the S-matrix for any physical system from the usual equations of electrodynamics" (quoted in Cushing, 1986, p. 122).

The fact that the Feynman fundamental equation is related to an individual term of the S-matrix expansion might mean that it is not relevant on its own (Rohrlich, 1999, p. 363). The point here is that there are strong arguments against the possibility of convergence of the power series expansion of the S-matrix (Aramaki, 1989, pp. 91-93). This led Dyson, who considered that quantum electrodynamics was the perturbative expansion itself, to conclude that "you didn't really have a theory" (quoted in Schweber, 1994, p. 565). It is possible to avoid this drastic conclusion and at the same time give relevance directly to a particular term of the S-matrix, and so to Feynman's fundamental equation, maintaining a view near Dyson's initial one. Considering the mathematical ill-definition of quantum electrodynamics as a 'fingerprint' for a physically motivated intrinsic approximative characteristic of quantum electrodynamics (Bacelar Valente, 2008a), it provides nevertheless under a few-order perturbative treatment the possibility of developing more or less direct applications from the basic theoretical framework that give good adjustment to experimental results. In this sense we have a 'working' theory, and the fundamental equation can be considered as having a meaning on its own, and not as simply related to a term of an non-realizable infinite expansion of an non-existing non-perturbatively determine S-matrix. A direct application of quantum electrodynamics through the fundamental equation is the derivation of Møller's formula for an electron-electron scattering. This is a simple model for an electron-electron interaction based on the exchange of one quanta between two electrons. We can consider improved calculations using higher-order corrections (Feynman, 1949b, p. 787). Simply – under the physically motivated mathematical ill-definition of the theory –, we are not obliged to use more complicated models that can be developed using the physical-mathematical framework of the theory, and the simplest option is probably

more elucidative regarding the physics hidden in the mathematics of the theory, in particular in this case where what is intended is the study of the temporal description of processes within quantum electrodynamics avoiding the problems of divergent integrals that appear in higher-order calculations (this question is addressed in Bacelar Valente, 2008b).

3. The description of interactions as space-time processes

In second-order expansion of the S-matrix the electron-electron interaction results from a photon interchange. In the overall space-time approach of Feynman we are considering virtual photon propagation between all the Minkowski space-time points. The Feynman photon propagator is given by

$$\left\langle 0\left|T\left\{A^{\mu}(x)A^{\nu}(x)\right\}\right|0\right\rangle = i\hbar c D_F^{\mu\nu}(x - x') \quad \text{(Mandl \& Shaw, 1984, p. 86).}$$

This expression means we are considering a photon 'created' at one space-time location and 'annihilated' at another. The use of the time-ordered product T{} means that in this covariant expression we are already considering, depending on the time order, a propagation from one electron to the other or the opposite, since $T\{A^{\mu}(x)A^{\nu}(x')\} = A^{\mu}(x)A^{\nu}(x')$ if $t > t'$, and $T\{A^{\mu}(x)A^{\nu}(x')\} = A^{\nu}(x')A^{\mu}(x)$ if $t' > t$. Loosely speaking we have contributions in which the 'emitter' and 'receiver' change roles.

The transition amplitude for the Møller scattering in second-order expansion of the S-matrix (the simplest for this process) results from a contribution of all possible localized interactions of Dirac and Maxwell fields 'connected' by a photon propagator (Mandl & Shaw, 1984, p. 113):

$$S^{(2)}(2e^- \to 2e^-) = \frac{-e^2}{2!}\int d^4x_1 d^4x_2 N\left[(\overline{\psi}^- \gamma^{\alpha}\psi^+)_{x_1}(\overline{\psi}^- \gamma^{\beta}\psi^+)_{x_2}\right] iD_{F\alpha\beta}(x_1 - x_2).$$

This means that the overall process we call 'interaction' results from the contribution of photon propagation from one electron to the other and vice versa: it is a two-way process in all space-time.

The 'virtual' label attached to the photon is related to two things. One is that in the space-time points where the photon is created or annihilated we have conservation of energy and momentum between the photon and the electrons. But the energy-momentum relation for the virtual photon is not $k^2 = (k^0)^2 - \mathbf{k}^2 = 0$ corresponding to a zero mass of the photon, but is different from zero due to the fact that in the expression for the propagator, $\mathbf{k}$ and k^0 are independent of each other (Mandl & Shaw, 1984, p. 86). In a certain sense it is like the 'dynamics' of the virtual photon (the same occurs with the electron when it is in the role of a virtual quanta) are all messed up, because it is like it has a mass during the virtual process. At the same time the 'kinematics' come out wrong also, because the propagator is non-vanishing at space-like separations (Björken & Drell, 1965, pp. 388-389). The other point is that this virtual quanta is supposed not to be observable by definition – it is part of the internal machinery of the model. In the case of the photon in the electron-electron scattering it seems difficult to avoid this situation, as implicit in the theory is the idea that this is the most elemental process possible. But as Feynman remarked "in a closed system all quanta can be considered as

virtual (i.e., they have a known source and are eventually absorbed)" (Feynman, 1949b, p. 182). This means that the label of 'virtual' or 'real' might depend on how we decide to separate what we consider to be the physical system and the measurement apparatus. Feynman stated this quite clearly:

> That this possibility exists can be seen from the consideration that what looks like a real process from one point of view may appear as a virtual process occurring over a more extended time. For example, if we wish to study a given real process, such as the scattering of light, we can, if we wish, include in principle the source, scatterer, and eventual absorber of the scattered light in our analysis. We may imagine that no photon is present initially, and that the source then emits light […] The light is then scattered and eventually absorbed […] that is, we start with no photons and end with none. Thus we can analyse the process by means of our formula for virtual process, and obtain the formulas for real processes by attempting to break the analysis into parts corresponding to emission, scattering and absorption (Feynman, 1950, p. 455).

That this possibility should be expected as a basic characteristic of any quantum theory is easily perceived if we recall Heisenberg's presentation of the physical principles of the quantum theory. When analysing the appearance of tracks of α-particles in a Wilson cloud chamber, Heisenberg remarked that "it appears purely as a matter of expediency whether the molecules to be ionized are regarded as belonging to the observed system or to the observing apparatus" (Heisenberg, 1930, p. 66). Even if this possibility is not applicable for the elemental process, it seems that there are processes where the change from "'virtual' to "'real' can be done. In this case, the virtual photon expressions can be translated into the 'correct' relations for real quanta, and are more an artifact of the theory than an 'defect' of the virtual quanta. In this sense the virtual photon is a more general concept than the real one, because "real processes corresponds to poles in the formulae for virtual processes. The pole occurs when $k^2 = 0$" (Feynman, 1949b, p. 781).

Another aspect of the description of scattering in quantum electrodynamics is that there really is no temporal description of the interaction in spite of the fact that in the formula there are contributions from photon emission and absorption by both electrons. This is due to the fact that in the application of the S-matrix method we are always considering the free initial and final states, while disregarding the detailed description of the intervening times. In this sense we have an atemporal description of the scattering processes. Feynman did not consider this a limitation; on the contrary, his view was that "the temporal order of events during the scattering … is irrelevant" (Feynman, 1949a, p. 749). In one aspect this is expected if we consider the interaction as an elemental process: a quantum theory only describes the probability distribution for the outcome of measurements of physical observables in specific experimental setups. And to compare quantum predictions with experimental results we need to obtain relative frequencies from repeated measurements (Falkenburg, 2007, p. 106). If we imagined we could see how the interaction was going on, we would be in a different – impossible – experimental setup from the actual existing experimental setup that permits the analysis of scattering processes.

When considering the interaction between two electrons, the S-matrix element is constructed with an underlying idea of an elapsing time. A (virtual) photon is emitted by one electron, which means that due to the localized interaction of the Dirac and Maxwell fields it is created at a specific space-time point. This photon propagates and luckily is absorbed by an electron expecting him. We have a sort of 'next' effect: the quanta 'knows' what is going to happen and behaves accordingly so that we have a

smooth adjustment between the electrons and the photon. In reality the sequence of creation and absorption of the photon is adjusted 'ab initio' in a mathematical expression the – S-matrix – that provides an atemporal description of what we consider to be a temporal phenomena. In a certain sense the problem is not in the adjustment of the creation and annihilation of the photon but in the use of temporal language in an atemporal description of the interaction in quantum electrodynamics, like when Feynman considered a situation where it was supposed that "one electron was created in a pair with a positron destined to annihilate the other electron" (Feynman, 1949b, p. 773).

If we try to maintain a temporal perspective considering, a bit incoherently with the usual interpretation of quantum theories, a submicroscopic observer – say Alice –, then the cat – our propagator – will reveal peculiar behaviours. The case is that the propagator does not vanish for a space-like separation. This means we would have an interaction between space-time points not connectable with a classical electromagnetic wave. But in this quantum world the photons and electrons (or positrons) being propagated between two points are not restricted by the usual energy-momentum relations, so we are beyond any classical dynamical description of the 'propagation', and, as mentioned previously, we refer to these quanta as 'virtual' while using the more realistic and ontologically charged word 'real' for the quanta whose energy-momentum relations are $k^2 = 0$ in the case of the photon and $p^2 = m^2$ in the case of fermions. For a submicroscopic observer located in the space-time point where a quanta is emitted we can imagine that an objective notion of present (emission) and future (absorption) exist. The problem is that for a space-like separation, a moving observer – Alice – might see the absorption before the emission. In the case of an electron propagation this would imply seeing a positron. The cat would be changing its form. Considering A. Einstein's kinematical interpretation of relativity (Einstein, 1905, p. 48), from the perspective of this moving observer – Alice –, that due to relativity can only make her observations using an (imaginary) submicroscopic classical electromagnetic wave, in the situation described above it would appear there is an interchange of the creation an annihilation points. In the case of photon propagation, this makes her think that the direction of propagation is the opposite, and in the case of electron propagation it will seem as if the unobserved quanta is now a positron. But even Alice, considering the kinematical interpretation of relativity, can only see the points of interaction between the fields, not the propagation process itself. In this way the 'true' virtual electron only appears to be a positron , but it is 'really' an electron.

When considering the overall amplitude, the problem fades away. The fact is that the S-matrix is covariant. So different 'observers' will obtain the same result for the scattering amplitude, with their identical submicroscopic experimental devices, when considering the propagation between all space-time points (a 'real' observer cannot make these space-time experiment to determine the scattering amplitude, he can only obtain experimental cross-sections). We can express the covariant S-matrix in two alternative forms (Sakurai, 1967, p. 204):

$$S_a^{(2)} = (-i)^2 \int_{-\infty}^{\infty} dt_1 \int_{-\infty}^{t_1} dt_2 H_I(t_1) H_I(t_2) \text{ , and } S_b^{(2)} = (-i)^2 \int_{-\infty}^{\infty} dt_1 \int_{t_1}^{\infty} dt_2 H_I(t_2) H_I(t_1) .$$

To see the content of these formulas let us consider localized 'observers' of processes that can be described by S_a. In this case we are considering processes where $t_2 < t_1$. Now,

a passer-by might, in relation to a spacelike propagation, think he is seeing a process where $t_1 < t_2$ as described in S_b. But he will also think that another process, that for the localized 'observer' is from S_b, is describe in S_a. The overall result will be the same for both observers. The possible time inversion problem does not occur as it is sweeped under the covariance of the S-matrix:

$$S^{(2)} = (-i/2)^2 \int_{-\infty}^{\infty} dt_1 \int_{-\infty}^{\infty} dt_2 \{H_I(t_1)H_I(t_2)\theta(t_1 - t_2) + H_I(t_2)H_I(t_1)\theta(t_2 - t_1)\},$$

where $\theta(t) = 1$ if $t > 0$, and $\theta(t) = 0$ if $t < 0$ (Sakurai, 1967, p. 204).

Going back to real observers, the fact is that we do not have a submicroscopic experimental access to the theoretical point-like interaction between the fields. In the case of scattering processes we have experimental access to the cross-section that "as an empirical quantity, it is the measured relative frequency of scattering events of a given type" (Falkenburg, 2007, p. 107). In quantum electrodynamics the scattering cross-section (as a theoretical quantity) is calculated from the transition probability per unit space-time volume, which is simply related to the S-matrix (Jauch & Rohrlich, 1976, pp. 163-167)

The point is that with the (experimentally accessible) cross-section calculated from the S-matrix – the only possible theoretical approach to scattering processes within quantum electrodynamics – we are not considering time as it goes by, but an atemporal calculation of the interaction process: all past and future are put in it. This is the problem, or limitation up till now, of the application of quantum electrodynamics to the description of interaction: it is basically outside time.

To recover some feeling of temporality we have to build a model of interaction that approaches a bit the ones provided by classical electrodynamics. To maintain things in quantum electrodynamics let us consider a positronium atom (formed by a positron and an electron). If now we consider the interaction of bound electrons, we do not have to consider all space. The photon is emitted in a certain region, where we can consider the atom to be. For clearly separated atoms we can get a notion of temporality from the sole propagation of a photon from one atom to the other. But with this kind of model we disregard the two-way character of the interaction, and approach the more classical modelling of radiation emission.

We consider that the emission from one atom takes place at a certain region V_y of space-time, meaning that the atom is in a certain location of space and that a photon with energy ω_0 is emitted during a period of time T. This photon is absorbed in the region V_x by another atom. We are going to take for granted for the moment that if the emission takes a time T then there will be an uncertainty $\Delta\omega$ in the energy ω_0 of the photon, so that we have $T\Delta\omega > 1$. At the same time we will consider only a situation where $\Delta\omega$ is much smaller that ω_0, which means that the sign of the energy is defined, and so it is clear that the energy is flowing out of the atom in V_y. We suppose we can adjust T so that $\Delta\omega \ll \omega_0$. From all this we have that $\omega_0 T \gg 1$. With this condition, considering "the part of S-matrix which is due to transitions in V_x and V_y" (Pauli, 1973, p. 134) and using explicitly the form of the wave functions of the bound electrons, every element of time in V_x is greater than every element of time in V_y. In this particular model we can from the S-matrix obtain a description of emission and absorption of a photon consistent with a notion of temporality associated with the process, but that is exterior to the S-matrix calculation. What the calculation provides is a definition of the

time relations involved and the spatial separation of the two regions that were from the start considered bound and separated in space-time. The result is that the two bounded regions do not overlap, so that we can say that "if the energy of the charged particles in V_x increases … and if the energy in V_y decreases, then V_x is later in time than V_y" (Pauli, 1973, p. 133). Also, the second region must be on the (diffuse) light cone of the first. Due to that, besides an uncertainty $\pm T$ resulting from "the uncertainty in the time of the emission process" (Thirring, 1958, p. 146), we have only contributions in the S-matrix from space-time points in regions that can be connected by photons propagating at light speed. This means also that for the distance r between the two atoms we have $r\omega_0 \gg 1$: the second atom must be in the wave zone of the first (roughly speaking a region where r is much bigger that the wavelength of the emitted photon: $r \gg \lambda$).

Maybe the most interesting aspect of this model is that in the wave zone we see that the contribution from the propagator comes from the poles, corresponding to a process with a real photon (Thirring, 1958, p. 146). As Feynman remarked "in a sense every real photon is actually virtual if one looks over sufficiently long times scales. It is always absorbed somewhere in the universe. What characterizes a real photon is that $k \rightarrow 0$" (Feynman, 1962, p. 95). We seen that the separation between virtual and real can depend not only on the way we choose what we consider to be the system but also on other aspects, like in the case of this model where it depends on the separation between the atoms: in the near zone ($r \ll \lambda$) the photons are virtual and on the wave zone they are real (Thirring, 1958, p. 146).

One point is clear from the previous case. To approach an idea of 'temporality' in models of interaction, using as a fundamental part quantum electrodynamics, we need structures in the models – the atoms – that permit the occurrence of real photons, which approach a more classical electrodynamics type of interaction (emission and posterior absorption of light). Also for a consistent outcome from this model it is necessary that $\omega_0 T \gg 1$ and this is not provided by the theory directly, because there is no time-energy uncertainty relation in quantum theories in the same sense as in non-relativistic quantum mechanics where there is an uncertainty relation between the position and momentum operators (Hilgevoord, 1996, p. 1451). We have to go and get it.

In the Maxwell-Lorentz classical theory we have a relation between $\Delta\omega$ – the line breadth – and the lifetime T of the radiation emission process. Considering "a linear harmonic oscillator as a simple model for a light source" (Heitler, 1954, p. 32), and taking into account the effect of the field produced by the charge on the charge itself (the self-force), the (emission) intensity distribution is given by

$$I(\nu) = I_0 \frac{\gamma}{2\pi} \frac{1}{(\nu - \nu_0)^2 + \gamma^2/4}$$ (Heitler, 1954, p. 33),

where ν_0 is the frequency of the undamped oscillator, and γ is the breadth at half of the maximum intensity and is equal to the reciprocal of the lifetime of the oscillator (due to the damping of the self-force the oscillator radiates during a period of time until it comes to rest). Considering that the reaction force is small we have that the lifetime is long when compared with the period of the oscillator, so that we have $\gamma \ll \nu_0$, that is, $\omega_0 T \gg 1$. Following the same approach when describing the decay of an excited state of an atom in quantum theory, again it is considered that "the lifetime is large compared with the frequency of the atom" (Heitler, 1954, p. 183), that is $\omega_0 T \gg 1$, and we obtain

the same expression for the intensity distribution of the emission (now as a probability function). In this way, we do not use any 'uncertainty' relation to obtain the result $\omega_0 T \gg 1$ that is needed to obtain a model for the interaction between the atoms that appears to give a consistent spatial-temporal description of the interaction. But it is important to notice that the quantum electrodynamics model is dependent on this previous quantum or classical treatment of the emission of radiation by an atom. We need the first atom to be in an excited state and the 'correct' line breadth as a starting 'ingredient', so that we are able to present in a plausible way in the S-matrix approach the type of temporal and spatial behaviour expected from classical electrodynamics.

Conclusions

It is clear that we only have access to a feeling of temporality associated with the description of interactions using the S-matrix when developing models that approach more classical situations.

The problem is that in a full quantum electrodynamics S-matrix calculations we really do not have a representation of scattering processes in space-time. We have an illusion of it, and from this, the incorrect perception that we have a description of processes in time. What we really have is a mathematical construction using as a basic structure the Minkowski space-time that enables us to obtain the cross-section for a particular scattering. But this theoretical cross-section is determined from the contribution of the Feynman diagrams in energy-momentum space, an ultimately it is this energy-momentum cross-section that is compared with experimental results (Falkenburg, 2007, p. 131).

We do have a description of the interaction in terms of quanta exchange between our observed 'particles'. What we do not have is an in space and through time description of this exchange. We have a quantum electrodynamics model based on a computational devise – the propagator – and a calculation based on a mathematical configurational space constituted by the Minkowski space-time points.

When we talk about a process we are using a temporal language. A process is something occurring in time and something that we can 'see' during its occurrence. If to the term process we associate some mathematical expression, like the Feynman fundamental equation, that would enable an apparent space-time 'visualization' of the process, we get the impression that we are 'seeing' things as they 'really' happen in space through time when doing calculations with the mathematical expressions. But for example when Feynman considers that "the Schrödinger (and Dirac) equation can be visualized as describing the fact that planes waves are scattered successively by a potential" (Feynman, 1949a, p. 751), he is using a language that is appropriate for classical waves in a improper context of a wave that (under the usual interpretation) represents the probability amplitude for a determined experimental outcome. So, this use is doubly improper. We have no classical wave, and the quantum wave does not describe the time development of the system in the same sense as in classical theory, it describes the time development of the probability distribution for a particular experimental outcome.

In the case of scattering experiments we have no 'insider' making observations, we have the initial state corresponding to a determined preparation of the system and the final calculated state that will enable us to make comparisons with the experimental results (Peres, 1984, p. 647). To have a path in space-time we cannot consider the

elemental interactions, because we cannot observe the internal configurational space where the interaction 'occurs' through the mathematical device of the propagator. Going back to Heisenberg and his α-particle in a Wilson cloud chamber, when each successive ionization of molecules of the medium is "accompanied by an observation of the position" (Heisenberg, 1930, p. 69), this sequence of observations reveals a path in space. But, in between each ionization the particle is described by a wave function. There is no microscopic trajectory. Each observation corresponds to a state preparation for the next one. It is the sequence of observations controlled by us that gives the notion of a process happening in time. In the case of Møller scattering we do not have that. It is a unique and global process associated with a sole experiment. It is not possible to visualize this process as something that is going on as we speak. Minkowski space-time has to be seen, when used in the context of S-matrix calculations, as a mathematical abstract space, where mathematical objects like the propagators are used as part of calculation machines. If we consider the scattering process as a 'black box' (Falkenburg, 2007, p. 234), it is the space-time itself that is this black box.

When considering an overall space-time approach we put ourselves outside this space-time. And since with any quantum theory we only have access to statistical predictions, there is not much we can say about the temporality of the phenomena as described by the theory.

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