Are Photons Essential?

Von Claude Cohen-Tannoudji, Paris*)

The purpose of this lecture is to discuss to what extent a quantum theory of radiation, using photons, vacuum fluctuations, field commutation relations etc. is essential at low energy (optical domain).

In order to demonstrate the efficiency of semi-classical approaches dealing with *quantized* atomic systems interacting with c-number *classical* fields, the lecture starts with a discussion of the photoelectric effect „without photons“ [1, 2, 3]. The probability of ionization of an atomic system by a monochromatic classical field can be calculated by standard time dependent perturbation theory. All important features of the photoelectric effect can be explained in this way. Furthermore, such a treatment can be extended to more complex situations (intensity correlations, coincidence rates etc.). For example, the probability to observe, in a classical stationary random field, one photoelectron at time t *and* another one at time $t + \tau$ is found to be proportional to the correlation function

$$P_2(\tau) = \overline{I(t) \cdot I(t + \tau)} \qquad (1)$$

of the light intensity. From such a relation, one can derive a semi-classical Schwarz's inequality

$$P_2(0) \geqslant P_2(\tau) \qquad (2)$$

which explains the „bunching“ of photoelectrons, first observed by Hanbury-Brown and Twiss, [4] without invoking photons and their boson character.

Actually, during the last decade, new photoelectric measurements [5–7] have been performed on the light emitted by a very small number of atoms, which have led to experimental violations of semi-classical inequalities such as (2). For example, one observes on the laser induced resonance fluorescence light emitted by a

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* *Prof. Dr. Claude Cohen-Tannoudji, Ecole Normale Supérieure and Collège de France, 24 rue Lhomond 75231 Paris Cedex 05. Extended abstract of a plenary lecture given at the 47th Physikertagung at Regensburg.*

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single atom, an "antibunching" of the photoelectrons, instead of a bunching [6, 7]. This shows that the light emitted by a single atom cannot be considered as a classical wave. Quantum-mechanically, such a result means that, after having emitted the first photon, the atom is in the ground state. In order to be able to emit a second photon, it must be reexcited by the laser, and this takes a certain time [8, 9, 10].

We then describe other semi-classical attempts for interpreting the previous results without field quantization. The idea is that any field comes from a source, and that the antibunching experiment tests the quantum nature of the emitting atom rather than the one of the light. More precisely, the field radiated by the atom is proportional to the atomic dipole moment D which is an *atomic operator* (we must take D and not its average value $<D>$ which is a c-number), so that the measurements of the field just reveal the quantum properties of the emitter. But we are then faced with the problem of spontaneous emission of radiation by an atom. What are the physical mechanisms of such a process? Is it possible to understand spontaneous emission by considering only the interaction of the electron with its own field (radiation reaction)? Are vacuum fluctuations and field quantization unessential for the emission process?

The general theoretical scheme, for discussing such a problem, is to derive, from the total hamiltonian, Heisenberg equations of motion for the field and electron variables. The integration of the field equations shows that the total field E at the electron position can be written as

$$E = E_f + E_s. \tag{3}$$

E_f is the "free" field which would exist even in the absence of electron (incident field and vacuum field). E_s is the "source" field which is radiated by the electron itself. It is then possible to identify in the electron equation the contribution of the interaction of the electron with the incident or vacuum field and the contribution of radiation reaction.

A first semi-classical point of view would be to treat E_f as a c-number (equal to zero in the vacuum) and E_s as an atomic operator. But this would introduce inconsistencies in the theory since electron commutation relations would not be preserved if E_f was not quantized [11]. Atoms would collapse! Furthermore, the quantized free field plays the role of a "Langevin force" in the electron equation, which cannot be ignored since damping and noise are *both* present in radiative processes (connection between fluctuation and dissipation) [10]. So, it is generally agreed that E_f must be quantized, for consistency, but vacuum fluctuations are still considered as unessential since, by choosing a particular order between commuting field and electron operators appearing in the electron equation (the so called normal order), one can present the electronic evolution as being due only to radiation reaction [12, 13].

The last part of the lecture is devoted to a refutation of such a point of view [14]. We show that the apparent indetermination in the separation of vacuum fluctuations and radiation reaction is removed by imposing to the corresponding rates of variation to have a well defined physical meaning (*hermiticity* requirements). This imposes the *completely symmetrical order,* rather than the normal one and leads to results which are in complete agreement with the usual pictures associated with vacuum fluctuations and radiation reaction. One finds, for example, that all radiation reaction affects are independent of $\hbar$ and strictly identical to those derived from classical radiation theory. They introduce a correction to the kinetic energy associated with the electromagnetic inertia of the electron. They produce a rate of emission proportional to the square of the acceleration of the radiating charge. On the other hand, all vacuum fluctuation effects, which are proportional to $\hbar$, can be interpreted by considering the vibration of the electron, induced by a random field having a spectral power density equal to $\hbar\omega/2$ per mode. In particular, they introduce a correction to the potential energy due to the averaging of the Coulomb potential seen by an atomic electron vibrating in vacuum fluctuations (Welton's picture [15]). Finally, the structure of the results is very general and can be expressed in terms of statistical functions of the two interacting systems (correlation functions C and linear susceptibilities χ). For vacuum fluctuation effects, one gets expressions of the form $C_F\chi_e$, which means that the field fluctuates (C_F) and polarizes the electron (χ_e), whereas, for radiation reaction, expressions such as $C_e\chi_F$ appear. The atomic electron fluctuates (C_e), polarizes the field (χ_F), i. e. produces a field, which reacts back on the electron.

Finally, we don't think that it is possible to ignore field quantization and vacuum fluctuations, even at low energy. This does not mean of course that semi-classical approaches are not interesting. In most cases, they provide the correct results in a short and simple way. One should rather consider these attempts for eliminating photons as a stimulation for new ideas, new physical insights and new experiments.

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