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The Fully Quantized Electromagnetic Field

Contents

Abstract

Einstein derived his coefficients of induced and spontaneous emission by assuming that electromagnetic radiation is directional, having the form of ”needle radiation”. That idea is extended here and shown to suggest a model of the atom in which excited atomic states are treated as three-body problems; nucleus, electron, and photon. The fully quantized electromagnetic field, or photon, is conceived of therefore as having a central core surrounded by a continuous sinusoidal field; and stimulated emission is the result of recoil momentum. ”Real” frequency doubling oscillators replace fictitious harmonic oscillators as the mechanism that connects excited atomic states with radiation fields. This allows the mathematical formalism of quantum mechanics to be assigned a more precise physical interpretation.

Evidence of the fully quantized electromagnetic field and frequency doubling oscillators is briefly described at the macroscopic level as well, by citing experiments from chaos theory and high speed photographs of spark discharges. The totality of the experimental evidence indicates that quantum phenomena occur when field sources are of balanced intensity while classical phenomena are the result of imbalanced intensities, i.e. when fields are describable by test charges.

1. Introduction

A fundamental difference exists in the way electromagnetic fields are detected in the classical and quantum theories. Classical fields are described by using test charges of vanishing intensity; whereas in quantum theory, due to the uncertainty principle, detectors of infinitesimal influence do not exist. This distinction is of particular importance in non-relativistic quantum mechanics where fields are treated as classical quantities and quantization is imposed only on the field energy. Full quantization of an atom's field was not carried out because as Bohr stated, “All our knowledge concerning the internal properties of atoms is derived from experiments on their radiation or collision reactions”[1], and the continuity of radiation fields could not be denied. Therefore Heisenberg dismissed Einstein’s view that radiation was needle-like, i.e. with directed momentum, when he formulated matrix mechanics. Let us review these questions more closely now to see if Heisenberg’s decision was justified, and if not to determine what quantum mechanics would be like had he used the Einstein radiation model.

2. Historical Perspectives

Quantum mechanics was not formulated in direct progression from a single inspiration or insight. Instead a series of seemingly disconnected contributions, theoretical and experimental, arrived in timely fashion to maintain continuous progress that required from inception to completion a mere 10 years. However, the collective effort that produced non-relativistic quantum mechanics would not have proceeded so smoothly, or so rapidly, were it not for the timely and highly incisive influence of Albert Einstein. This is because both wave and matrix mechanics have their origin in concepts that he introduced.

Indeed the founding principle of wave mechanics was an extension to material particles by de Broglie of concepts developed in the 1905 papers on special relativity and the photoelectric effect. Einstein also provided a stimulus towards completion of these ideas in a series of papers on the quantum theory of gases by showing that the same statistics Bose had applied to light quanta could also be used to describe a gas of material particles[2]. This led in direct succession to Schrödinger’s development of wave mechanics and to the first paper on quantum electrodynamics by Dirac introducing the concept of second quantization[3].

Einstein also participated in the initial development of the matrix formulation of quantum mechanics with his paper on the induced and spontaneous emission of electromagnetic radiation[4]. However, because there are extensive differences in the mathematical formalism of these theories, the extent of his influence is seldom appreciated. Nevertheless analysis reveals that ”all subsequent research on absorption, emission, and dispersion of radiation was based upon [this] paper”[5].

3. The Qquantization Methods of Einstein and Heisenberg

3.1. Theoretical Differences

The matrix formulation of quantum mechanics was arrived at by analyzing the relationship between discrete atomic energy states and the continuous time-averaged fields of electromagnetic radiation. Thus the radiating atom is conceived of as emitting a spherical wave with no net momentum transfer. On the other hand, Einstein derived his coefficients of emission and absorption under the assumption that electromagnetic radiation consists of localized quanta of energy $h\nu$ and momentum E/c, such that ”outgoing radiation in the form of spherical waves does not exist”[6]. Clearly there are fundamental differences in the physical origin of these two mathematical models. The Einstein emission theory treats electromagnetic radiation as a distribution of localized energy quanta with directed momentum, or “needle rays”, whereas the Heisenberg theory is based on a continuous wave interpretation.

The only means we have for understanding atomic processes is to analyze the radiation that the atom emits so it is not surprising that Einstein had a deep-rooted, long lasting dissatisfaction with the form that quantum mechanics took. Less known is the fact that Einstein’s paper on induced and spontaneous emission had not appealed to Heisenberg either[7]. He only made use of its results after he had incorporated the idea that the atom consists of a two-fold infinite, denumerable array of virtual oscillators[8]. Such a model does not, however, reflect momentum transfer between atom and radiation field. Instead momentum is derived by means of a quantum mechanical reformulation of the classical Fourier series representing position coordinates. This yields the commutation relation,

$$\mathbf{pq} - \mathbf{qp} = i\hbar.$$

On the other hand, Einstein described radiation processes by using a model that treats energy and momentum equivalently. The intimate connection that exists between his model of emission and absorption, and the conservation laws caused Einstein to conclude.

Almost all theories of thermal radiation are based on the study of the interaction between radiation and molecules. But in general one restricts oneself to a discussion of the *energy* exchange, without taking the

[1] N. Bohr, ”The Como Lecture” (1927), in *Symposium on the Foundations of Modern Physics* , P. Lahti & P. Mittelstaedt (eds.), (World Scientific, 1987), p. 7.

[2] A. Einstein, ”Quantum theory of one-atom ideal gases”, *Sitzungsberichte Preussische Akademie der Wissenschaften* (1924), p. 261; (1925), p. 3.

[3] J. Bromberg, “Dirac’s quantum electrodynamics and the wave-particle equivalence”, in C. Weiner (ed.), *History of Twentieth Century Physics*, (NY: Academic, 1977), p. 147.

[4] A. Einstein ”On the quantum theory of radiation” (1917), in B.L. van der Waerden (ed.) *Sources of Quantum Mechanics*, (Amsterdam, 1967), p. 63.

[5] Ibid., p. 4.

[6] Ibid., p. 76.

[7] J. Mehra & H. Rechenberg, *The Historical Development of Quantum Theory*, Vol. II (NY: Springer, 1982-1988), p. 176.

[8] Ibid., p. 176 ff.

momentum exchange into account. One feels easily justified in this, because the smallness of the impulses transmitted by the radiation field implies that these can almost always be neglected in practice, when compared with other effects causing the motion. For a *theoretical* discussion, however, such small effects should be considered on a completely equal footing with the more conspicuous effects of a radiative *energy* transfer, since energy and momentum are linked in the closest possible way[9].

If Einstein is correct then momentum exchange is important in a theory of emission and must be placed on an equal footing with energy exchange to satisfy the conservation laws. However, at the time there was no direct evidence linking momentum transfer to the emission and absorption processes and thus no need to account for needle radiation.

3.2. Experimental Evidence

Although the momentum exchange between matter and radiation fields could not be detected in 1926, experimental techniques eventually improved and this changed rapidly. Studies of the phenomenon of nuclear magnetic resonance demonstrated that correlated states in nuclei lead to the angular and spatial correlation of photons, which is then manifested as coherent radiation[10]. The observed coherence is attributed to "photon recoil momentum" and it anticipated the existence of a similar effect in optical phenomena. This was confirmed experimentally through the observation of intensity fluctuations of partially coherent light[11]. Thus photons emitted spontaneously may generate coherent pulses of small cross sectional area and extremely high intensity within a partially coherent (or incoherent) beam of much lower time-averaged intensity. The phase of the spontaneous emissions is random while the induced radiation, or photon bunch, is correlated. The direction of emission and phase of each of the correlated photon bunches is determined therefore by that of a spontaneously emitted photon. In contrast, the matrix model of atomic energy states is obtained by assuming a spatially and temporally uniform, spherically symmetric distribution of energy. We seek a model of the atom that accurately reflects the experimentally observed *instantaneous* distribution of energy and momentum in radiation fields such that both the continuous and discontinuous aspects of radiation are taken into account.

[9] A. Einstein (1917), in B.L. van der Waerden (ed.), pp. 76-7.

[10] R.H. Dicke, "Coherence in spontaneous radiation processes", *Physical Review* **93**, 99 (1954).

[11] R. Hanbury Brown & R.Q. Twiss, *Nature* **177**, 27 (1956).

4. The Fully Quantized Electromagnetic Field

4.1. Stimulated Emission by Recoil Momentum

If the assumption is made that emission occurs in the same way for both nuclear and atomic systems; then stimulated emission is a result of photon recoil momentum. To maintain the existence of such a mechanism is unreasonable unless both the incident photon and the quantized energy of an excited atomic state have particle-like properties. The excited hydrogen atom is conceived of therefore as a union of three particles: proton, electron, and photon. This is an acceptable physical model since very fine semiconductor powders have already been used to localize light to a volume on the order of the wavelength[12]. Thus the excited atomic state may be regarded as an extension to atoms of the experimentally observed phenomenon of photon localization. The three body model provides a simple explanation for why atoms obey Bose-Einstein statistics and also dispenses with the need for the quantum "jump" of electrons. A photon's absorption displaces the electron into a state of higher potential while emission causes it to "fall" back[13].

The localized energy quantum, or photon, is conceived of as having independent existence in the same way as other particles. Its structure consists of a central core of length λ and period $1/\nu$ that is surrounded by one cycle of a sinusoidal electromagnetic field. Generalized coordinates are unable to represent point particles in motion relative to a fully quantized field. Therefore it is ultimately the independent existence of the photon that prevents the atomic electron from following classical equations of motion. The commutation relation may be interpreted as a mathematical statement describing the merged properties of electron and photon. Non-commutativity can then be explained by the fact that the photon occupies a volume $\hbar$ of phase space when in a bound state.

4.2. The Electron Oscillator

The linear harmonic oscillator cannot be used as a physical model to describe emission by recoil momentum since it is only able to reproduce continuous oscillatory motion. We replace it with the electron oscillator, one cycle of which is defined to be an electron's displacement into a different energy state and its subsequent return to the original state. A different physical interpretation of the energy matrix

[12] S. John, "Frozen light", *Nature* **390** , 661 (1997)

[13] There is ample experimental evidence that the free photon has an impenetrable core. This is assumed to be true of photons in a "bound state" as well.

$A = a_{ij}$ is now required. The off-diagonal elements, i $\neq$ j, give one complete cycle of an electromagnetic wave and one-half cycle of the electron oscillator. The diagonal elements of the array, i = j, represent one complete cycle of the electron; and include both absorption, i.e. photon capture, and emission.

One complete cycle of the electron oscillator is equivalent to two complete cycles of an electromagnetic wave, or two photons, and results in a doubling of the frequency of oscillation. This is the linear analogue of what occurs when the state function of a half odd integer spin particle is rotated through 4π radians, or two complete cycles[14].

5. Physical Interpretations

5.1. Mathematical Formalism

Quantum mechanics is conceived of as a special case of the more general problem of finding the equations of motion of an independent system containing three field sources. A solution of the three body problem is only possible by performing two successive mathematical operations. First, a composite of any two vector fields is obtained (the state vector) giving an infinite number of possibilities (the probability amplitudes). The influence of the third vector field (the operator) is then applied giving an infinite number of possible values for the physical variable (the eigenvalues). Combining the vector fields in a different order gives two distinct, but mathematically equivalent solutions: matrix and wave mechanics.

5.2. Quantum Electrodynamics

Dirac created the idea of a "zero state" to account for the disappearance of the photon by absorption and its subsequent reappearance by emission[15]. These processes are represented formally by the creation and annihilation operators. However, if photons are captured by the atom rather than destroyed, they may be interpreted as descriptions of the transition from an observable free state to an unobservable atomic state. Similarly "second quantization" is interpreted as the separation of the wave function into its physical components, electron and photon. All are formal expressions that describe transformations between fully quantized fields and fields quantized in energy alone.

5.3. The Frequency Doubling Oscillator

Energy quantization in the form of discrete energy states has been verified by means of a great number and variety of experiments, yielding extremely accurate results. A different set of physical features characterizes the fully quantized field; and though not of a quantitative nature they too are easily recognizable and occur with great frequency. The most visible characteristic is frequency doubling. Frequency doubling occurs when an electron is driven by an external field between discrete energy states thereby generating photons whose field has at least twice the frequency of oscillation of the field driving it. Frequency doubling has been observed when very small temperature differences are applied to liquid helium[16].

The period doubling that occurs at the onset of chaos may be interpreted as the result of a driven electron oscillator. This is because a doubling of the frequency of oscillation doubles the number of periods observed in a rest frame. In other words, electron dipole transitions are produced by many superposed electromagnetic waves thereby causing the period of the oscillation to double. Period doubling during the route to chaos is therefore a result of energy flowing from continuous to discrete forms by means of the direct involvement of molecules.

5.4. The Non-local Action of Forces

The force that is transmitted by an electromagnetic field is currently believed to be a consequence of the creation and annihilation of energy quanta by field sources, the material particles. However, if force is the manifestation of a fully quantized field then it causes both particles to pivot about a common center. Rather than the electromagnetic field of one particle acting at the location of a second particle, force is conceived of as acting on both particles/field sources simultaneously. This would occur in a manner similar to the way gravitational forces act by "curving" space rather than by directly altering particle motion. Therefore the fully quantized field is external to and between the field sources.

Evidence of a fully quantized electrostatic field has in fact been observed. If oppositely charged spheres are brought together, a spark will jump across neutralizing the field between them. It is possible to record the discharge with a Kerr cell during the first billionth of a second of formation, and it reveals that instead of starting at the point of highest field strength the spark is initiated in the middle and goes both

[14] see L.I. Schiff, *Quantum Mechanics* , (NY: McGraw-Hill, 1968), p.205.

[15] P.A.M. Dirac (1927), "The quantum theory of the emission and absorption of radiation", in J. Schwinger, ed., *Selected Papers on Quantum Electrodynamics*, (NY: Dover, 1958), p. 18-19.

[16] A. Libchaber, "Experimental study of hydrodynamic instabilities. Raleigh-Benard experiment: Helium in a small box", in *Nonlinear Phenomena at Phase Transitions and Instabilities*, T. Riste (ed.), (NY: Plenum, 1982), p. 259.

ways[17]. Due to the linearity of the electromagnetic field this experiment represents a simple magnification to macroscopic proportions of field effects that occur within the hydrogen atom. It demonstrates that force is not exerted at the location of particles, but at a point midway between them whose location depends upon the relative field strength of the sources. Therefore Coulomb's law is an approximation that only applies in cases of large field imbalance when the test charge approximation is valid.

6. Conclusion

The three body model of excited atomic states is meant as an initial step towards an improved understanding of atomic processes rather than as a completed theory. It is an attempt to imagine a return to the 1920's to ask how quantum mechanics would appear today had Bohr and Heisenberg wholeheartedly embraced Einstein's concept of needle radiation. Thus it is an invitation to renew the painstaking progress that Einstein had achieved towards defining the nature of the photon in a series of papers during the period from 1905 to 1917[18]. Would Dirac, as one of the principal authors of quantum mechanics, have approved of replacing its present form with a derivation based on the views of Einstein? In fact he predicted that this would happen.

I was more interested in getting the correct equations. It seemed to me that the foundation of the work of a mathematical physicist is to get the correct equations, that the interpretation of those equations was only of secondary importance ... It seems clear that the present quantum mechanics is not in its final form ... I think it is very likely, or at any rate quite possible, that in the long run Einstein will turn out to be correct, even though for the time being physicists have to accept the Bohr probability interpretation, especially if they have examinations in front of them.[19]

Therefore the use of an electromagnetic field quantized in both energy and momentum provides a means for reinterpreting the physical meaning of equations that Dirac and others have derived. It does not refute the Bohr probability interpretation, rather it shows that the reason probabilities are needed is to enable a system of three particles with continuously intersecting electromagnetic fields to be described by a series of equations.

The main features of the theory are as follows:

1. The photon has a discrete length and period, and is surrounded by a continuous sinusoidal electromagnetic field.
2. Once created the photon may be physically transformed, but not destroyed.
3. Due to the indestructibility of the photon Heisenberg's well-known statement, "quantum mechanics [is] founded exclusively upon relationships between quantities which are in principle observable"[20] receives as its corollary; *all quantum mechanical observables include photons.*
4. Field sources of imbalanced intensity behave classically, while field sources of balanced intensity exhibit quantum mechanical behavior.

It is hoped that this model of the excited atomic state will stimulate progress in new areas of research, both theoretical and experimental.

[17] E.L. Andrews, *Optics of the Electromagnetic Spectrum* , (Prentice Hall, 1960), p. 459.

[18] A description of these papers may be found in, A. Pais, *Subtle is the Lord, The Science and Life of Albert Einstein,* (Oxford University Press, 1982), p. 402 ff.

[19] P.A.M. Dirac in *Albert Einstein, Historical and Cultural Perspectives*, G. Holton & Y. Elkana (eds.), (Princeton University Press, 1982), p. 79.

[20] W. Heisenberg (1925), "Quantum theoretical reinterpretation of kinematic and mechanical relations", in B.L. van der Waerden (ed.), *Sources of Quantum Mechanics.*