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Anti-photon

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Abstract. It should be apparent from the title of this article that the author does not like the use of the word "photon", which dates from 1926. In his view, there is no such thing as a photon. Only a comedy of errors and historical accidents led to its popularity among physicists and optical scientists. I admit that the word is short and convenient. Its use is also habit forming. Similarly, one might find it convenient to speak of the "aether" or "vacuum" to stand for empty space, even if no such thing existed. There are very good substitute words for "photon", (e.g., "radiation" or "light"), and for "photonics" (e.g., "optics" or "quantum optics"). Similar objections are possible to use of the word "phonon", which dates from 1932. Objects like electrons, neutrinos of finite rest mass, or helium atoms can, under suitable conditions, be considered to be particles, since their theories then have viable non-relativistic and non-quantum limits. This paper outlines the main features of the quantum theory of radiation and indicates how they can be used to treat problems in quantum optics.

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The underlying science of light is called the Quantum Theory of Radiation (QTR), or Quantum ElectroDynamics (QED). There were hints of this subject in W. Heisenberg's first papers on matrix mechanics of 1925, but the real foundation came in P. Dirac's work of 1927. At first, only a few people needed to know much about the quantum theory of radiation. With the conception, in 1951, of the ammonia-beam maser by C. Townes, the making of the ruby optical maser by Th. Maiman and the helium-neon gas laser by A. Javan, W. Bennett and D. Herriott in 1960, and a flood of other devices soon afterward, there was a population explosion of people engaged in fundamental research and in very useful technical and commercial developments of lasers. QTR was available, but not in a form convenient for the problems at hand. The photon concepts as used by a high percentage of the laser community have no scientific justification. It is now about thirty-five years after the making of the first laser. The sooner an appropriate reformulation of our educational processes can be made, the better.

1 A short history of pre-photonic radiation

Modern optical theory [2] began with the works of Ch. Huyghens and I. Newton near the end of the seventeenth century. Huyghen's treatise on wave optics was published in 1690. Newton's "Optiks", which appeared in 1704, dealt with his corpuscular theory of light.

A decisive work in 1801 by T. Young, on the two-slit diffraction pattern, showed that the wave version of optics was much to be preferred over the corpuscular form. However, so high was the prestige of I. Newton, that the teaching of optical physics at Cambridge University only changed from corpuscular to wave optics in 1845.

There were also the discoveries by A.-M. Ampère (1820, 1825), H. Oersted (1820) and M. Faraday (1831) of electromagnetic phenomena in the first half of the nineteenth century, which culminated in the publication of the treatise on electromagnetic theory in 1864 by J. C. Maxwell. With the discovery of electromagnetic waves by H. Hertz in 1887, there could be little doubt that light had a wave rather than a corpuscular nature.

By the time of his inaugural lecture [3] as Cavendish Professor at Cambridge University in 1871, J. C. Maxwell had recognized that matter had to have an atomic structure. He foresaw that integral numbers and probability theory would play a role in the new physics. Unfortunately, Maxwell died in 1879, at the age of 48! During the last decade of the nineteenth century, a number of new and very unexpected things were discovered: electrons, positive ions, X-rays, radioactivity and the photoelectric effect.

A theory of matter could be based on the atom model of J. J. Thomson (1904), in which electrons moved in

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It is a pleasure to join in the 60th birthday celebration of the Director, Herbert Walther, of the Max-Planck-Institute for Quantum Optics at Garching, and wish him much happiness and many more years of his very great scientific creativity an extended spherical distribution of positive charge associated with a positive ion. An atom consisted of electrons bound electrostatically to the ion. The potential energy for an electron in this kind of atom could only be calculated if the positive charge density were known as a function of radius from the center of the ion. The most plausible guess would be that the potential near the center of the ion was a parabolic function of radius, which would lead to simple harmonic-oscillator motion. At larger radii, the potential would flatten out. One could hope to calculate the spectrum of radiation emitted by an excited atom, and to give an account of photoelectric removal of an electron by external radiation. It would have been very hard for the physicists of the time to deal with the necessary problems of nonlinear mechanics. Even if they could have done so, the results would have been hopelessly in discord with observations. A widespread attempt in this direction might have delayed the development of physics for many decades.

The spectral distribution of thermal black-body radiation was treated by Lord Rayleigh (1900) and J. Jeans (1905), using classical electromagnetic theory and statistical mechanics. They obtained agreement with observations at long wavelengths, but there was an ultraviolet catastrophe. The results did not agree with the displacement law of W. Wien (1893), or the later observations of O. Lummer and E. Pringsheim (1990), and H. Rubens and F. Kurlbaum (1901).

In 1900, M. Planck tried to check on the derivation of the Rayleigh law. In doing so, he replaced an integration over the frequencies of the radiation, $\int d\nu \ldots$, by a discrete sum, $(kT/h)\sum \ldots$, where k was Boltzmann's constant, T the absolute temperature, and a new constant h, now called after Planck, which was a quantity with dimensions of an "action" (an energy multiplied by a time, or a momentum multiplied by a distance). Thus was born the light quantum of radiant energy, the beginning of the quantum theory. It took over a quarter century before any kind of adequate theoretical description of these phenomena could be found. Even today, near the end of the twentieth century, most people are still confused even about the meaning of non-relativistic quantum mechanics, or the multitude of sub-nucleonic phenomena, and the latest theory of everything is still far from being the final solution of anything. After this gloomy statement about physics in the twentieth century, I return to the chronological discussion of historically necessary, but sometimes logically unfortunate events.

Shortly after 1900, alpha-particle emission was studied by E. Rutherford and co-workers at Cambridge. The exponential law for radioactive decay was established. This led E. von Schweidler in 1905 to the recognition that there could be no casual explanation of alpha-particle emission. The data implied that a Markoff process was involved, i.e., the laws governing the emission had to be probabilistic, rather than deterministic. Of course, a probabilistic approach was also vital for A. Einstein's 1905 work on Brownian motion in diffusion theory.

Everybody knows that 1905 was a good year for Einstein. He also worked on the photoelectric effect. (Light quanta: Particles again, for the second and (hopefully) last time.) By 1905, a number of important observations had been made on photoelectric phenomena. In 1839, E. Becquerel observed that the voltage of a voltaic cell could be changed by shinning light on an electrode. W. Smith discovered the photoresistivity of selenium in 1873. H. Hertz found in 1887 that electromagnetic radiation emitted from a spark gap could be changed by illumination with ultraviolet light. A year later, W. Hallwachs observed that a clean insulated zinc plate acquired a positive charge on illumination with ultraviolet light. Under such conditions, a negatively charged plate lost its charge, even in high vacuum. Also, in 1900, J. Elster and H. F. Geitel found that the photoelectric current was proportional to the intensity of illumination, with no detectable time lag. In 1902, P. Lenard discovered that the maximum kinetic energy of photoelectron depended in a linear fashion on the frequency of the light, but was independent of its intensity. Nobody found any way to make the Thomson model of the atom account for any of these strange phenomena. The Einstein light-quantum hypothesis fitted in very well with the above observations. However, Einstein was unable to calculate the rate of photoemission of an electron from either an atom or a metal surface. Shortly after the First World War, R. Millikan made much more accurate studies of the basic phenomena mentioned above. In 1929, E. Lawrence and J. Beams showed that the time lag between irradiation and photoemission was less than 5×10^{-9} s. To date, three Nobel prizes have been awarded for work connected with the photoelectric effect: to Lenard in 1905, to Einstein in 1921 and to Millikan in 1923.

E. Rutherford (1911) used a nuclear atom model to explain large-angle scattering of alpha particles by matter. (The word "proton" was coined by Rutherford in 1920). The obvious conclusion was that electrons in atoms were like the planet in a solar system. The overwhelming difficulty was, that, according to the current electrodynamic theory, the accelerated electrons would radiate energy and rapidly spiral into the nucleus.

N. Bohr (1913) applied phase-integral quantization to a one-electron nuclear atom. Attempts to deal with many-electron atoms failed, and the model was of no help to chemical valence theory.

In a discussion of a black-body radiation in 1917, A. Einstein introduced the A coefficient for the rate of spontaneous emission by atoms, and a B coefficient for their absorption of radiation. He also introduced a "new" process of stimulated emission of radiation, and found that the above B coefficient determined its rate. It is easy to see why Einstein accepted a spontaneous radiative-decay rate A from one atomic state to a lower one. He knew that there was a similar process in which alpha particles are emitted by heavy nuclei. Also, the Bohr theory of 1913 postulated spontaneous transition between stationary states of atoms.

The B coefficient for absorption of a light quantum by an atom was taken over from the model of the photoelectric effect. Einstein found that to get the correct thermodynamic description of black-body radiation he had to insert another term in his rate equations so that when a light quantum interacts with an excited atom, a second light quantum is emitted (stimulated emission of radiation). There is no way that anything like spontaneous transitions [4] from one atomic stationary state to another can come from classical electromagnetic theory applied to an electron in a model atom. However, as I have pointed out elsewhere [5], the classical Maxwell electrodynamics already made provision for both of the B coefficients. Whether a charge q moving with velocity v in an electric field E will gain or lose energy depends on the algebraic sign of the product qEv. If the charge is gaining energy, the electromagnetic field must be losing energy (that is equivalent to absorption of radiation). If the charge is losing energy, the electromagnetic field must be gaining energy. That is equivalent to stimulated emission of radiation. Only the relative directions of the v and E vectors determines the direction of energy flow between field and matter. It would have made for much better physics if Einstein had recognized this fact, and had used his theory to calculate the value of the A coefficient for spontaneous emission in 1917, instead of leaving it to Dirac in 1927 to get the A coefficient from the quantum theory of radiation.

In the domain of electronics, a triode vacuum-tube radio-frequency oscillator was developed by L. De Forest in 1912. This was, in fact, the first maser oscillator made by man. A theory of this oscillator was given by E. V. Appleton and B. van der Pol [6] in 1921. Needless to say, the theory was completely classical, and made no use of the quantum of radiant energy. It did, however, mention the concept of "negative resistance". No one could foresee its consequences. Only the end of the Second World War would bring atoms and vacuum tubes together. Einstein's work clearly led to the Townes maser development of 1951 and the work of C. H. Townes and A. L. Schawlow later in the decade. Other stepping stones [7] on the path were provided by R. Tolman (1924) (negative absorption), R. Ladenburg (1929) (negative dispersion), W. E. Lamb and R. Retherford (1946–1947) (negative absorption), and C. H. Townes and A. L. Schawlow [8] (beginning to get the message).

In retrospect, it is clear that Einstein got things somewhat turned around. He should have accepted Maxwell's equations because they were invariant under a Lorentz transformation. However, it is clear that he did not trust them for interaction processes between radiation and matter, as shown in his discussion of the photoelectric effect. He should have taken spontaneous emission as the new feature which required more attention, and not stimulated emission as he did. Still, it might be that the laser was discovered sooner than it would have been if Einstein had not brought attention to what seemed to him to be the obscure process of stimulated emission.

We now come to two years of great progress, in which W. Heisenberg, E. Schrödinger and P. Dirac developed matrix mechanics, wave mechanics and quantum mechanics, in 1925–1926 and M. Born (1926) introduced the probability interpretation of the absolute square of the wave function in order to discuss particle-scattering experiments.

G. Wentzel (1926) and G. Beck (1926) showed that the new quantum theory could describe the photoelectric effect correctly, without any use of "photons" or light quanta, using only a classical time-dependent electromagnetic field. They made use of first-order quantum mechanical perturbation theory applied to an atom. Their theory gave all of the features required by Einstein in 1905, and, in addition, gave an expression for the rate of the photo process. Of course, in 1905 and in 1917, Einstein did not have quantum mechanics (and would not have liked it if he had). In the 1926 work of Wentzel and Beck, the energy of the ejected photoelectron was given by the frequency-resonance condition of the perturbation theory when its equation was multiplied throughout by Planck's constant. The energy $\hbar v$ of a photon did not enter the calculation in any way, only its frequency v. This problem was given as an exercise in L. Schiff's text book on Quantum Mechanics. Much later, W. E. Lamb and M. O. Scully [9], and H. Fearn, and W. E. Lamb [10] made more detailed calculations on the atomic photoelectric effect.

2 The photon of G.N. Lewis

G. N. Lewis [11], in 1926, coined the word "photon" to describe something completely different from the Einstein light quantum. The word "photon" caught on, but not Lewis's meaning. Lewis was a physical chemist educated at M.I.T. who was, for about thirty years, starting in 1912, the founding Dean of the College of Chemistry at the University of California, Berkeley. He became a member of the U.S. National Academy of Sciences in 1913, and resigned in 1934 over some issues of policy.

Lewis was a very gifted physical chemist, and knew a lot of classical, but non-quantum, theoretical physics. He understood very well that the Bohr orbits of 1913 could not possibly describe the rich body of phenomena associated with the word "valence". We know now that quantum mechanics is required for this, and also the knowledge that electrons have spin and obey the Fermi–Dirac statistics. Chemical interatomic forces involve the part of their electrostatic interaction associated with the phrase "Heitler–London exchange energy". In 1916, in work independent of similar research by I. Langmuir and A. Kossel, Lewis had formulated an electron-pair theory of chemical affinity. This was based on D. Mendeleyev's Periodic Table. A molecule like H_2 is stabilized because the two electrons can sometimes have a strong attraction for each other. By 1926, Lewis knew that electrons have spin angular momenta and magnetic moments. He thought that the magnetic forces were sufficiently strong to give the chemical forces. In fact, the magnetic forces are far too small, but Lewis was looking for a theory of chemical valence. He had no way to anticipate the later work of W. Heitler and F. London. Lewis would, given an excuse, consider substantial changes in the physical properties of elementary particles, like electrons and protons, if that would advance the theory of chemical valence.

In 1926, Lewis sent several rather obscure letters to the editor of Nature. In one [12], he speculated that the transmission of radiation from one atom to another was carried by a new particle, for which he coined the name "photon". This was to Lewis a real particle which could be bound to an atom. He specifically denied that it was the light quantum of Planck, Einstein and Bohr. Furthermore, the title of the letter was "The conservation of photons", and this was certainly not a feature of the light quantum. Lewis only mentioned the wave-like properties of radiation in passing, and attributed them to some kind of guiding ghost field. In retrospect, it seems to me that Lewis should have had his photon be the source, and sink, of Maxwellian radiation.

I will briefly mention three other episodes from Lewis' career. In the very early thirties, I attended a Berkeley seminar on valence theory given by L. Pauling. This was presided over by Lewis, who did not believe a word he heard, and gave Pauling a very hard time. Pauling made no mention of Heitler and London, but made frequent misuse of the word "resonance", which in physics has a much broader meaning than the mere exchange of energy between two coupled pendulums.

In 1936–1937, Lewis [13] had the idea that the scattering of neutron waves by atoms required that there be strong forces between neutrons and electrons. Knowing that light scattering is related to the index of refraction, Lewis though that there ought to be neutron refraction by matter which could scatter neutrons. He therefore constructed lens-shaped objects made of paraffin, and thought that he could detect a focusing of neutrons in his laboratory. In such work it is important to keep the neutrons from being reflected from other objects in the room. To this end, the source–lens–detector system was enclosed in a cylinder made of cadmium sheets, since that element was known to strongly absorb neutrons. Eventually, it turned out that cadmium also is a strong scatterer of neutrons, and the neutrons reflected from the cadmium overwhelmed any refraction by the paraffin lens. During my eight years in Berkeley, I had just one conversation with Lewis, in 1937, when he called me into his office to give some advice. It was: "When a theorist does not know what to do next, he is useless. An experimental scientist can always go into his laboratory and "polish up the brass". In return for this advice, I told him that according to meson theories of nuclear structure there would only be a very small electron–neutron interaction. (See, for example, a partial account of my Ph.D. thesis [14].) Neither of us then took the proffered advice. Of course, we now know from later work by I. I. Rabi, W. Havens and J. Rainwater [15], and by E. Fermi and L. Marshall [16], that there really is a short-range force between electrons and neutrons. This produces very important effects in experiments with cold neutrons, but would not have contributed to a detectable effect in Lewis' work. Shortly before his death in 1946, with post-docs like M. Calvin and others, Lewis [17] was doing very nice and pioneering work on triplet states of molecules.

With the unfortunate word "photon" so well established, it was inevitable that a similar word "phonon" would be introduced in 1932 for quantized vibrations in a solid. Nevertheless, in 1939, I was able to give a theory [18] of the Mössbauer effect without use of the word "phonon".

3 A short history of post-photonic radiation

In 1927, P. Dirac developed the Quantum Theory of Radiation (QTR).

In 1929, W. Heisenberg and W. Pauli gave a much more elaborate formulation of QTR than Dirac, but did not really add much to the usefulness of the theory.

J. R. Oppenheimer (1930) pointed out that QTR led to infinite integrals when higher-order processes were considered.

E. Wigner and V. Weisskopf (1930) calculated the radiative decay spectral line shape. They also had infinities, but gracefully swept them under the carpet.

E. Fermi (1932) made a great contribution to QTR in his Reviews of Modern Physics article, especially for a treatment of Lippmann fringes. The technical details of the present article will be difficult for a reader who has not understood what Fermi die with Lippmann fringes. G. Lippmann received the Nobel prize in 1908 for use of his fringes in an early form of color photography. The material in Fermi's article came from a 1930 Theoretical Physics Summer School at the University of Michigan at Ann Arbor, which was organized by G. Uhlenbeck and S. Goudsmit. Fermi also showed that the radiation emitted by one atom and absorbed by another travelled with the speed of light. His work was somewhat flawed by the divergent integrals of his perturbation theory, but physical insight brought him to a plausible answer.

The first book on applied QTR was that by W. Heitler [19] (1944, 1954). The first edition had nothing useful to say about the self-energy problems. Neither edition had anything about masers or lasers.

At the first of the 1960's Rochester Coherence Conferences, I suggested that a license be required for use of the word "photon", and offered to give such a license to properly qualified people. My records show that nobody working in Rochester, and very few other people elsewhere, ever took out a license to use the word "photon". It reminds me that there was once a phlogiston theory of heat, which began to go out of style about the time that people at Cambridge University stopped using the corpuscular optics of Newton.

My concern was ignored. For example: In a 1969 Scientific American collection "Lasers and Light", G. Feinberg [20] stated that "What the laser does is to produce vast numbers of particles of exactly the same energy and wavelength. With no other stable particle but the photon is such a feat possible. The laser beam's remarkable macroscopic properties arise that its constituent particles are precisely identical. Whether the laser could have been invented without quantum mechanics is an interesting question". And, "At present the photon theory gives an accurate description of all that we know about light". Feinberg's article stimulated the 1972 paper "Classical Laser" by M. Borenstein and W.E. Lamb [21] which showed that a laser could be completely classical. It was not really necessary to prove this, since the first realistic semi-classical theory [22] of gas lasers was published in 1964. A similar theory [23] using QTR appeared in 1967, and no particles like "photons" appeared in it at all.

Many books began to appear on quantum electronics and optics. Thus:

R. Loudon [24] (first edition, 1973; second edition, 1983; Book on QTR, post-laser, lots of photons); M. Sargent, M.O. Scully and W.E. Lamb [25] (first edition 1974; third edition, 1976; "Laser Theory", very few photons), and C. Cohen-Tannoudji, J. Dupont-Roc and G. Grynberg [26] "Processus d'Interaction entre Photons et Atoms" (1988) and "Introduction to Quantum Electrodynamics" (1989).

4 Structure of quantum theory of radiation

A radiation field is a dynamical system that has to be treated according to the laws of quantum mechanics with a Hamilton operator

$$H = \int (E^2 + B^2)\, d\tau'.$$

Here, $d\tau' = dx'dy'dz'$ is a three-dimensional volume element,

$$E = E(x', y', z', t) \text{ and } B = B(x', y', z', t)$$

are an infinite number of time-dependent quantum-mechanical operators for the electric and magnetic fields which are labeled by their space point x', y', z'. The E and B operators obey certain commutation rules guessed at by analogy from Heisenberg's matrix mechanics for a material, but fictitious, particle. The field E is analogous to the x coordinate of the particle, and the B field to the momentum p of the particle.

Instead of working with a threefold continuum of labels x', y', z', it is usually more convenient to expand the x', y', z' dependence in things like Fourier-expansion function. Thus, we write

$$E(x', y', z', t) = \sum E_k(t)\, v_k(x', y', z',),$$

where the $E_k(t)$ are quantum-mechanical operators. The $v_k(x', y', z')$ are normal modes of vibration which are classical functions of x', y', z' like $\sin(kx')$ which solve an appropriate boundary-value problem.

A mode k of the radiation field is mechanically analogous to a one-dimensional simple harmonic oscillator. Its Hamiltonian might be written as

$$H = \frac{1}{2}\left(\frac{p^2}{\mu} + \mu\omega^2 x^2\right),$$

where μ is an effective mass, ω is a suitable circular frequency, x and p are Cartesian coordinate and momentum, respectively, of the radiation oscillator's pseudo "particle". The k labels a mode, i.e., a degree of freedom, of the electromagnetic field. Each $v_k(x', y', z')$ is a classical function of x', y', z' determined by solving a classical boundary-value problem for the electromagnetic field with the appropriate linear optical hardware-like mirrors, lenses, prisms, diffraction gratings, beam splitters, etc. Instead of using x', y', z' as a label we can use k. Depending on the problem, k might be a scalar or a vector quantity. If any of the optical hardware involves nonlinear elements, some kind of disagreeable perturbation theory will be required. Elements with loss will have to be modeled in some convenient fashion.

Examples of optical problems requiring the introduction of normal modes are shown in Figs. 1–8:

1 A closed optical resonator with perfectly conducting walls in the shape of a rectangular parallelepiped, or as shown in Fig. 1, an ellipse boundary for a two- (or three-)

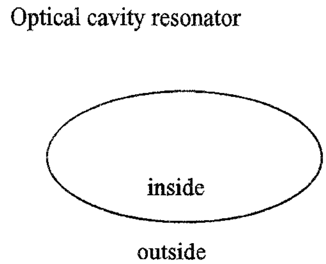

Fig. 1. A closed optical resonator with perfectly conducting walls

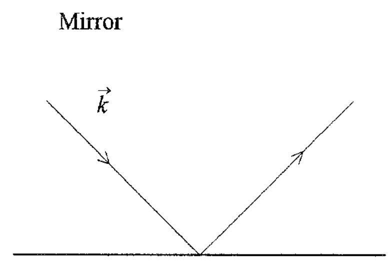

Fig. 2. Reflection (half space above a perfectly reflecting plane mirror)

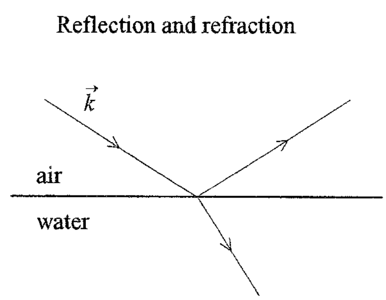

Fig. 3. Reflection and refraction at a plane interface between two media of different indices of refraction

dimensional problem. Two distinct problems are possible: the inside, or the outside problem. The former would have discrete eigenfrequencies and eigenfunctions, and the latter would have a continuous spectrum. If desired, a window could be modeled by replacing part of the metallic boundary by a thin dielectric boundary.

2 Reflection (half space above a perfectly reflecting plane mirror, as treated by Fermi in his discussion of Lippman fringes). A particular normal mode is indicated schematically by the incident and reflected rays (Fig. 2). The mode functions v_k themselves are not shown, but they are implied by the ray labelled by k. Each of the rays, incident, reflected, refracted or diffracted, makes a contribution to the corresponding mode function v_k. The mode label k appears only on the ray for the incident plane wave. The functions v_k are obtained from the solution of the boundary-value problem. Read the Fermi article, or forever go on thinking that photons exist.

3 Reflection and refraction at a plane interface between two media of different indices of refraction (Fig. 3). The modes are consistent with Snell's law.

Beam splitter

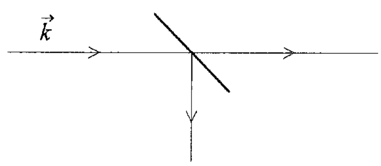

Fig. 4. A simple beam-splitter problem

Frustrated internal reflection

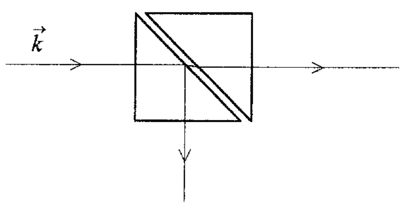

Fig. 5. Two prisms cut from a cube of glass and configured so as to give an example of frustrated total internal reflection

Young's 2 slit diffraction pattern

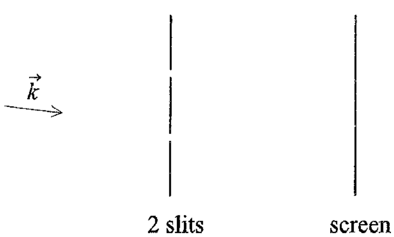

Fig. 6. A Young's two-slit diffraction arrangement

4 A simple beam-splitter problem (Fig. 4). Note that for the single mode k, there are electromagnetic-field regions both to the right of the beam splitter and below it.

5 Two prisms cut from a cube of glass and configured so as to give an example of frustrated total internal reflection (Fig. 5). Tunnelling of the mode fields across the gap plays an important role in the calculation. Note that the single incoming wave k leads to a mode function that has finite field values both below and to the right of the cube.

6 A Young's two-slit diffraction arrangement (Fig. 6). A plane wave k incident from the left turns into two contributing parts of the v_k on the right-handside of the screen with two holes.

7 A typical laser configuration of two Fabry-Perot plates (Fig. 7), perhaps treated by the method of G. Fox and T. Li. When the **k** vector is at right angles to the mirrors, the problem becomes much simpler, and has been treated by simple analytical approximations by Spencer and Lamb [27], and by Lang, Scully, and Lamb [28]. With three or more mirrors, one could have a ring-laser resonator [29].

Fabry-Perot

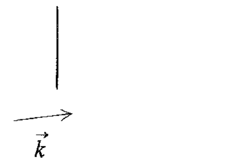

Fig. 7. A typical laser configuration of two Fabry-Perot plates

Interferometer

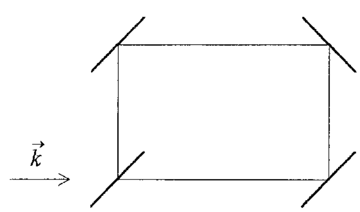

Fig. 8. Any of a large number of multi-port devices reminiscent of a Michelson interferometer

8 Any of a large number of multi-port devices reminiscent of a Michelson interferometer (Fig. 8).

Only the first of these problems could have discrete normal-mode solutions of Maxwell's equations. In the other cases, there would be a continuous spectrum of modes, each of which might be characterized by having an incoming plane-electromagnetic wave characterized by a propagation vector **k**, together with appropriate reflected, refracted or scattered waves. In case 7, there would be the Fox and Li quasi-modes for certain ranges of the **k** vector.

I hope to have made it clear that a quantum-mechanical radiation field is dynamically equivalent to a system of quantum-mechanical simple harmonic oscillators. It is therefore important to enumerate the possibilities for states of such a system.

5 System of simple harmonic oscillators in quantum mechanics

5.1 Types of states for a single simple harmonic oscillator

(i) Eigenstate of energy $E_n = \left(n + \frac{1}{2}\right)\hbar\omega$.

The eigenfunctions $u_n(x)$ involve Hermite polynomials. This is wave mechanics of a particle with a single Cartesian coordinate called x. See a good text book on quantum mechanics for pictures of the stationary-state wave functions.

(ii) Coherent superposition of eigenstates. Non-stationary states, or wave packets,

$$\psi(x, t) = \sum c_n u_n(x) \exp\left(-\frac{i}{\hbar} E_n t\right).$$

(iii) Mixtures, described by a density matrix, not a wave function.

5.2 *Types of states for a system of N simple harmonic oscillators*

The coordinates are written as $x_1, x_2, x_3, \ldots, x_N$, respectively. The wave function of this many-body problem can be a product of N functions of the types (i) and (ii) above, or even worse: linear combinations of such products.

One could also have mixtures of such pure-case states.

6 Characteristics of states of the radiation field

Each mode of the field is dynamically equivalent to a simple harmonic oscillator. If only one normal mode of the field is being considered, we have the complexity of cases (i), (ii) and (iii) above. The normal-mode functions are functions of space coordinates x', y', z'. The dynamical coordinate describing a single-mode electromagnetic field might be conveniently described by a symbol like E. This is analogous to the coordinate x of a simple harmonic oscillator, but now x is used for a field-point coordinate in classical Euclidian space, so that the symbol E is used for the quantum-mechanical system of the single-mode radiation field. If N modes of the radiation field are considered, the possible complexity is as described above for a system of N linear simple harmonic oscillators. Now we will have "coordinates" E_k for each of the N normal modes.

6.1 *Radiation field with one mode*

If only one mode k of a radiation field is being considered, and if that mode is in a number state, i.e., we have an eigenstate of energy

$$\left(n_k + \frac{1}{2}\right)\hbar\omega_k,$$

and it makes a kind of sense to talk of a state of n_k "photons". The appearance of the $\frac{1}{2}\hbar\,\omega_k$ zero-point energy is only a minor embarrassment. If we have a superposition state with a wave function of the form

$$\psi(x,t) = \sum c_n u_n(x) \exp\left(-\frac{i}{\hbar} E_n t\right),$$

we have to talk about probabilities $|c_n|^2$ for "finding" a certain number of photons in that mode. Photons cannot be localized in any meaningful manner, and they do not behave at all like particles, whether described by a wave function or not.

6.2 *Radiation field with several modes*

We have just mentioned that a "one-photon state" would be a state of the radiation field with *only one* excited mode. However, it is possible to have a need for more normal modes. Consider the problem in which there is initially one excited atom in an unbounded region which can undergo spontaneous transitions to a ground state. The radiation field has an infinite number of modes (which we may label with an index like k). This is the Wigner–Weisskopf problem. Those authors calculated the rate for spontaneous radiation. They did not calculate the wave function for the atom–field problem, but could easily have done so. When this problem is treated in the standard Wigner–Weisskopf manner, one finds that at large time, the wave function for the radiation field will be a time-dependent linear combination of one-phonon states (i.e., one additive term for each k). Each of the additive wave-function terms will be an infinite product of photon-number states, and each such product will be characterized by one k with $N_k = 1$, and the rest of the N_ks equal to 0. Except in an approximate way, the resulting state is not a one-photon state.

With more complicated states it is terribly difficult to talk meaningfully about "photons" at all. QTR gives the only proper description. The wave function of the system will be a function of the coordinates E_k of the radiation oscillators. The operator for the electric-field operator $E(x', y', z', t)$ at a space point-time x', y', z', t will contain creation and destruction operators for the various normal-mode functions $u_k(x', y', z')$ which are required for the optical hardware of the problem.

7 What do we do next?

We should, and can, use the Quantum Theory of Radiation to analyze the problem we have, and to get answers to physically meaningful questions. Fermi showed how to do this for the case of Lippmann fringes. The idea is simple, but the details are somewhat messy. A good notation and lots of practice makes it easier. Begin by deciding how much of the universe needs to be brought into the discussion. Decide what normal modes are needed for an adequate treatment of the problem under consideration. Find a suitable approximation for the normal modes; the simpler, the better. Decide how to model the light sources and work out how they drive the wave function for the system. Also decide how the one or more photo detectors are coupled to the system. When the news is good: The system is described by a wave function. Consider how the wave function evolves, and the effect the quantum field has on the detectors. When the news is bad: The system is describable only by a density matrix. Find out what the pure-case constituents are, and treat each of them, properly weighted, as above.

Using the wave function of the system, one can obtain various probabilities and also such things as expectation values of the electric field operators, or products of the field operators which would be needed for calculations involving photoelectron currents. One can use the quantum description of the field to work out the desired photocounting statistics. To some extent, that has already been given by R. Glauber [30], but not for the complete generality which might someday be required.

8 Winding down

There is a lot to talk about the wave–particle duality in discussion of quantum mechanics. This may be necessary for those who are unwilling or unable to acquire an understanding of the theory. However, this concept is even more pointlessly introduced in discussions of problems in the quantum theory or radiation. Here the normal mode waves of a purely classical electrodynamics appear, and for each normal mode there is an equivalent pseudo-simple harmonic-oscillator particle which may then have a wave function whose argument is the corresponding normal-mode amplitude. Note that the particle is not a photon. One might rather think of a multiplicity of two distinct wave concepts and a particle concept for each normal mode of the radiation field. However, such concepts are really not useful or appropriate. The "Complementarity Principle" and the notion of wave–particle duality were introduced by N. Bohr in 1927. They reflect the fact that he mostly dealt with theoretical and philosophical concepts, and left the detailed work to post-doctoral assistants. It is very likely that Bohr never, by himself, made a significant quantum-mechanical calculation after the formulation of quantum mechanics in 1925–1926.

9 Summary

It is high time to give up the use of the word "photon", and of a bad concept which will shortly be a century old. Radiation does not consist of particles, and the classical, i.e., non-quantum, limit of QTR is described by Maxwell's equations for the electromagnetic fields, which do not involve particles. Talking about radiation in terms of particles is like using such ubiquitous phrases as "You know" or "I mean" which are very much to be heard in some cultures. For a friend of Charlie Brown, it might serve as a kind of security blanket.

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