Abstract Title

Antiphoton: Electromagnetic radiation and nano-materials.

Symposium Track

1. Fundamental Modeling in Nanomechanics

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INTRODUCTION

Authors often comment that a proper description of the interaction of light and matter requires that the electromagnetic (EM) field be treated quantum mechanically as well as the matter, often leading to an analysis using Schroedinger's equation and a quantized optical field. A "proper" description of the system thus uses an approximate (i.e., non-relativistic) description of the matter. The reason, of course is that a proper relativistic description is harder than an approximate, non-relativistic one, and the additional effort is only warranted if it improves the agreement of theory with experiment. In fact, it is no more inherently necessary to use a fully quantum mechanical treatment of light interacting with matter than it is to use quantum chromodynamics to describe planetary orbits. There is a large body of work using the so-called semiclassical approximation, in which matter is treated quantum mechanically (typically by Schroedinger's equation) and the EM field is treated classically. i.e, using Maxwell's Equations[1-20]. The greatest part of this body of work describes the extremes of scale in matter: simple atomic and molecular systems or macroscopic (i.e., bulk) systems. Much of it shows explicitly that the results of the semiclassical approximation give the same results as the fully quantized calculations[21-38]. The question at hand is whether these results transfer directly to nanoscale systems. In short, is it necessary to quantize the EM field when it interacts with a nanoscale system? I explore this question in a roundabout way. First, I discuss the common view of the photon held by some physicists and most other scientists. Next, I review the semiclassical approximation and some physical systems that have been successfully described by it. I then provide an overview of the actual quantum theory of the EM field, constrasting it with commonly held view. Finally, I do not answer the question posed. I rather charge the audience to answer it.

THE PHOTON

The commonly held view of the quantum of radiation is that light actually consists of a barrage of tiny particles, each carrying a tiny amount of energy. A beam of light consists of so many 'photons' as to appear as a continuous beam of energy, much the way a stream of water seems continuous, though it consists of tiny molecules (actual example from actual classroom). This model appears in Albert Einstein's description of the photoelectric effect (as well as his uncelebrated description of the Stoke shift), which presumably explains the appeal. The similarity of the word 'photon' to the names of actual particles, such as the electron, proton or neutron, fosters this interpretation. It is the misleading nature of this word that motivates my objection. (Similar complaints can be lodged regarding the word phonon -- but I digress).

THE SEMI-CLASSICAL APPROXIMATION

Claims of the "particle" nature of light stem invariably from quantized energy transfer. That is, the energy transferred from the EM field to matter is given by $\Delta E = h\nu$. What could be more telling than the frequnecy of the light - a wave property - appearing right next to Planck's constant, h? I submit that this relation is more properly written: $\nu = \Delta E / h$, as the following discussion makes clear. Solving Schroedinger's equation for the material system provides the stationary states of that system. The oscillating EM field, treated classically according to Maxwell's equation, creates new states that are mixtures of the old. But transitions between two of these states is possible only if the frequency of the classical field, ν, matches the oscillation of the mixed state: $(E_f - E_i)/h$. Thus, $\nu = \Delta E / h$. This semiclassical approximation (and its cousin, the "neoclassical" approximation) suffices to describe a great many phenomena, including: the photoelectric effect (and other absorption processes, including multiphoton processes), the action of lasers (i.e., stimulated emission), and Compton scattering, as examples. On the other hand, this is the semiclassical approximation. It fails for other important processes: spontaneous emission (which the SC approximation says should not happen) and the Lamb shift.

THE QUANTUM THEORY OF RADIATION

Electromagnetic radiation is quantized in the way that matter is: by constructing a Hamiltonian and identifying the conjugate variables, and then imposing upon the conjugate variables a commutation relation (i.e., invoking the uncertainty principle). Two significant differences in the case of EM fields are that a Hamiltonian density rather than a Hamiltonian is constructed, and that there is no position operator in the Hamiltonian. The problem is formally the same as a harmonic oscillator and can be solved analogously, with the difference that it is the energy density rather than the energy that is quantized. But, more significantly, like the harmonic oscillator, the minimum energy (or energy density) is nonzero. It is this nonzero EM field that explains spontaneous emission and the Lamb shift. At the same time, it provides a virtual infinity of mass-energy for cosmologists to worry about.

FINAL WORDS

One can generally comment that the semiclassical approximation works whenever the number of elementary EM excitations is large (i.e., many photons), corresponding to the classical idea of a large field amplitude. Conversely, it fails when the classical field is small (or zero!). And there are contradictions to both of these conclusions. Speaking as one who works in the "original" nanotechnology - the field of polymers and macromolecules - there seems to be nothing inherent in nanoscale systems that requires a quantum theory of radiation.

Keywords

QED, semiclassical, photon, radiation

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