Quantum mechanics was born out of Planck's struggle to understand the behaviour – or from a classical viewpoint, misbehaviour – of radiation. Over the years, most physicists have got used to thinking of atoms, molecules and solids in quantum terms but, paradoxically, photons still leave many uncomfortable. Prof. G. W. Series, himself a leading contributor to the experimental study of matter and light in interaction, expresses his feelings on some of these matters in this article. He does not question the outstanding experimental successes of quantum electrodynamics in its closer sphere but makes a plea for the study of alternatives, such as the Wheeler–Feynman absorber theory, which handle self-fields, the vacuum and other concepts in a way that may be found more physically appealing. Indeed, it is a revelation that considerable work has already been done on these lines by a small band of enthusiasts. This may appeal to some of our readers. Perhaps there are also others among them who will rise to the defence of the orthodox (and enormously successful) textbook point view, and it will be interesting to hear from them. After all, what is at stake is nothing less than giving the electromagnetic field a special, privileged role in our view of the world rather than embedding it in the all-encompassing framework of quantum theory.

—Editor

Sparks in the dark: Sidelights on quantum optics

G. W. Series

A critical eye is cast upon too-easy notions of photons and the concepts of the quantized electromagnetic field. Classical fields still have much to offer. The spontaneous emission of light by atoms must include radiation reaction as a physical cause. The Absorber Theory of Radiation, whose quantized formulation is based upon the quantization of atoms, forms an alternative to the conventional Quantum Theory of Radiation. Ultimately, radiation must be a branch of cosmology.

What is a photon?

Might it be said, perhaps, about photons, that familiarity breeds contempt? No, I would not argue that. But I would ask whether familiarity does not deaden the critical faculty. Your wavy line labelled *hv*, for example. It is shorthand, isn't it? But shorthand for what? And how many of us are content to live with *hv* as the first and last statement about photons?

Consider, for example, the photoelectric detection of a short pulse of light—let it be from a highly monochromatic (but low power) laser, say, in the neighbourhood of 5×10^{14} Hz. And let the pulse be 1 ps long, so that the spectral width is at least 10^{12} Hz. What, then, is ν, when the pulse allows only a few hundred oscillations to pass? Well, we can easily deal with that. We simply make a wave packet, a coherent superposition of monochromatic waves. But then we have to deal with phases and amplitudes, so what has become of our little bundles of energy labelled *hv*?

I came across coherent superpositions in the *emission* of light in the nineteen fifties, when we were applying the (then) new 'optical radio-frequency double resonance' technique to free atoms in a vapour; the atoms were excited by a lamp emitting resonance radiation while an oscillating magnetic field at radio-frequency in resonance with a Zeeman structure in the excited states, produced by a static magnetic field, was applied to the vapour. The fluorescent light from the atoms was strongly modulated at the r.f. frequency. How was one to interpret this on the photon picture? The atoms were radiating independently of each other, by spontaneous emission. But each atom was in a superposition, induced by the continuous-wave r.f. field, of the Zeeman states. On the picture, then, that each atom emitted its photon independently of the others, every photon was a coherent superposition of two frequencies, $\nu \pm \frac{1}{2}\delta$, where δ was the r.f. frequency. Moreover, although these photons were being emitted at random times, the phase relations within the superposition were such that the net effect of many such photons was a strong modulation at δ. This was, for the ordinary physicist, an unfamiliar state of affairs, though there was nothing fundamentally remarkable in it for your sophisticated quantum field theorist. He would express an arbitrary radiation field as a superposition of modes of plane waves of sharp frequency, extending throughout space and

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time. The modes (basis states of the field) are specified by a wave vector, a polarization vector, a frequency and an occupation number, n. The energy of the eigenstate n is $(n+\frac{1}{2})h\nu$. The state $|\psi\rangle$ of an arbitrary radiation field is characterized by a particular set of amplitudes:

$$|\psi\rangle = \sum_{n=0}^{\infty} c_{n,\nu}|n,\nu\rangle.$$

Such formalism is sterile until we describe the interaction with matter. The emission of a photon $h\nu$ by an atom is represented mathematically by a change $|(n+\frac{1}{2}),\nu\rangle \rightarrow |(n+1+\frac{1}{2}),\nu\rangle$, which, in the case of spontaneous emission, is $|(\frac{1}{2},\nu)\rangle \rightarrow |(3/2,\nu)\rangle$. All components ν of the field participate in this number change to the extent quantified by their probability amplitudes in the superposition.

Good, now we know what photons are: changes in the occupation number of a basis state in a mathematical expression.

And the physics? What about that click from the loudspeaker coupled to the photocell when you open the shutter to your pulse of light? Isn't that a beautiful demonstration of the physical reality of photons? No, sir. What you heard was the working of a bit of acoustical apparatus triggered by an *electron. You have no evidence of photons until you allow them to interact with matter.* Best leave them as mathematical entities!

The ground state of the radiation field

Let us return to the states labelled $n=0$. These are energy eigenstates: their energy is $\frac{1}{2}h\nu$, for all ν. Quite a familiar notion, the ground state energy of a harmonic oscillator. Mathematics. Is there any physics in it? Yes, there is: a lot of physics and a lot of trouble and a lot of double-talk.

Some of the physics we have already met. A radiation field in these states, interacting with atoms in excited states, can induce them to emit light. We call it 'spontaneous emission' because it occurs without any externally applied stimulus. The atoms can be in a black box at absolute zero. All lamps, all heat sources are turned off. The box is evacuated save for a few atoms, and in the vacuum an atom goes 'pop' and spits out one of those wavy lines labelled $h\nu$. Surely *something* must interact with the atom to make it explode.

Yes, the theorists say, the vacuum really isn't empty at all. It's full of radiation in states $n=0$. For each frequency there is zero-point energy and that means that there are electric fields in the vacuum. We can't tell you anything about the strength of the fields or the phase of the fields, but we can tell you the mean square field strength: it is $\langle E^2\rangle = 16\,h\pi\nu^3/c^3$ per mode. So, first double-talk, a vacuum isn't a vacuum. 'Nothing's plenty', to quote the splendid title of an exceptionally good expository article[1].

But isn't it plain as daylight that, whatever you might claim to be *in* a vacuum, you can't take anything *out*? Hold! Not so! Clever physicists *can* take something out. It was done, after a fashion, a good many years ago, but quite patently, and with remarkable skill, more recently[2]. How do you get rid of stray electric fields? By screening. Very well, then, can we get rid of the zero-point electric fields by screening? Yes, we can: they did. Conducting plates, very close together (separation d) such that standing waves of wavelength greater than $2d$ could not be sustained between them. Even the zero-point modes were suppressed. Proof: the spontaneous emission at wavelengths greater than $2d$ was suppressed from beams of excited atoms travelling between the plates. Beautiful experiments. You *can* control spontaneous emission: you *can* change the properties of the vacuum, it would appear.

But stop again. We changed the characteristics of spontaneous emission of light from atoms by bringing up conducting plates close to them. We explained this by saying we had altered the zero-point radiation field around them. But if we hadn't known all that sophisticated quantum field theory, might we not have offered the explanation that the conducting plates themselves, being so near to the radiating atoms, might have been the cause of what we observed? Let us consider the atoms constituting the conductors. Let us admit the quantization of matter (we are suspending judgement, for the time being, on the radiation field, not on the quantization of matter). Those atoms in their ground states possess, it can be admitted, fluctuating electric dipole moments, hence, emit fluctuating electric fields. Might not *these* be the source of the stimulus which causes the atoms in the beam to emit spontaneously, or not to emit, if particular modes are suppressed? Answer, yes. The argument can be carried through quantitatively[3].

Now, back to our quantized radiation field, permeating all space and time. In the conventional theory it is treated as a *free* field. But, insofar as this field, modified between conducting plates, might equally well have been replaced by a field *radiated* by neighbouring matter, is it possible that the all-pervading free field of conventional theory might be replaced by a field emanating from matter? Yes, that can be done, too. It is supposed that, that part of the universe which we study is surrounded by absorbing matter; absorbing and radiating: The Absorber Theory of Radiation. It has been presented in a variety of ways since its first formulation in terms of classical electromagnetism[4]. A recent account has been given by Pegg[5].

Our intention is not to disparage the conventional quantum theory of radiation, some of whos recent successes we shall mention later, but to warn against its uncritical acceptance as the *only possible* theory. One alternative we have just spoken of. Let us pursue the objective of seeing how far a less sophisticated theory might carry us.

But first, before we leave the ground state of the quantized radiation field, we mention one other set of phenomena which has received a great deal of attention, which has called for some extraordinary mathematical devices of challengeable validity for its working out, and which, nevertheless, has had some stunning successes: the phenomena of atomic energy level shifts. Strictly speaking, as Pancharatnam pointed out many years ago[6], these shifts, commonly thought of as radiative corrections to the energies of free atoms, should be understood as contributions to the energy of the combined system, atom plus zero-point radiation field. Within the limits of this article we shall not be able to discuss level shifts in addition to spontaneous emission. It is enough to recognize that, for a time-asymmetric interaction such as we have under consideration (or have we?—that is a point about which whole books have been written), the level shifts are dispersion conjugates of spontaneous emission. The one implies the other.

Classical fields

An elementary description of the free electromagnetic field is in terms of modes $\mathbf{E}=\mathbf{E}_0 \cos(\omega t-\mathbf{k}\cdot\mathbf{r})$, and correspondingly for the magnetic component. The so-called semi-classical theory of radiation allows fields described in this way (quantum-mechanical *c*-numbers; that is to say, ordinary numbers, not operators) to interact with quantized atoms (or other constituents of matter) by means of an interaction Hamiltonian $\mathbf{E}\cdot\hat{\mathbf{P}}$, where $\hat{\mathbf{P}}$ is a vector operator (electric dipole moment) acting on the wave-function representing the atom. (Some authors prefer $\mathbf{A}\cdot\hat{\mathbf{p}}$, where $\mathbf{A}$ represents the vector potential of the field and $\hat{\mathbf{p}}$ a vector operator representing momentum. There are subtle questions of gauge to be considered in comparing these two forms).

It is to be understood straightaway that this treatment describes stimulated processes only, absorption and emission. *It does not*, without some further interaction which we must discuss, *describe spontaneous emission*. But the parts of physics where the $\mathbf{E}\cdot\hat{\mathbf{P}}$ interaction is powerful and sufficient are numerous and important; they are the fields in which the stimulated processes are dominant because the wavelength of the radiation is very much greater than the physical size of the interacting particle and the energy of the radiation field is very much greater than the exchanges of energy taking place in the individual particle interactions (in quantum terms, when the occupation number n is large compared with 1). We need only recall nuclear magnetic resonance and its applications, not only in studying the properties of nuclei but in solid state physics, in industrial physics, in medical physics. We recall also electron spin resonance which again permeates industrial physics and chemical physics as well as fundamental laboratory physics. And the laser: the first theories of operation of the laser were worked out with $\mathbf{E}_0 \cos(\omega t-\mathbf{k}\cdot\mathbf{r})$. So, incidentally, was the theory of the Compton effect[7]. The beauty of this treatment—highly successful in all the fields we have mentioned—is the prominence given to the phase of the field. Consider, for example, the various pulse and spin-echo techniques in n.m.r.; how phase is of the essence. The same is true for the laser. It would be wrong, however, to suppose that phase cannot be brought out in quantum field theory. In the energy eigenstates themselves the phase is completely hidden. But it can be exhibited by building superpositions of energy eigenstates to form, for example, what are called 'coherent states of the field'. These must be used with great care since they form an over-complete set. The point we are making is that the semi-classical theory exhibits phase in an obvious way in each basis mode of the interaction. Moreover, this approach to calculating radiative interactions forms a convenient bridge between the noble edifice of classical electro-magnetism and quantized matter[8].

Semi-classical treatment of spontaneous emission.

Undoubtedly the semi-classical theory fails for sufficiently high frequencies and for sufficiently weak fields if the *c*-number fields are written solely to represent the laboratory-generated electric and magnetic fields. To describe spontaneous emission it is essential to recognize the existence of some further field capable of interacting with the radiating object. One need not justify this by appealing to the zero-point field of quantum field theory: the requirement lies in classical electromagnetism itself. The motion of a radiating oscillator is damped: it loses mechanical energy to balance the electromagnetic energy radiated. By equating the two losses, or by looking carefully at the field as it interacts with different elements of the source, one can discover the magnitude of the force which damps the motion—the radiation reaction force, or, equivalently, a reaction field. This field must be added to the laboratory-generated field to complete the semi-classical theory[9]. The reaction field leads to *spontaneous emission* and level shifts; the laboratory-generated fields lead to *stimulated emission and absorption*.

The literature on the radiation reaction field is enormous. There are serious conceptual difficulties in classical electromagnetism when one approaches the limit of a vanishingly small source, and questions of pre-acceleration arise, connected with the fact that the reaction force turns out to be proportional to $\dddot{\mathbf{r}}$; the third time-derivative of the position vector. Some of these difficulties can be resolved by building the theory upon a time-symmetric version of electro-magnetism. (It will be recalled that the conventional theory of radiation from an oscillating charge discards the negative-time solution of Maxwell's equations for no reason arising out of the mathematics, but because it *does not* accord with experience.) Wheeler and Feynman accepted the negative time solution and formulated a classical, time-symmetric Absorber Theory of Radiation[4]. We have already referred to a recent form of this[5], built upon quantized atoms. Pegg works with a time-displaced Hamiltonian representing *direct action* between emitting and absorbing atoms. Hoyle and Narlikar, earlier, had given an action-at-a-distance formulation of interactions between particles[10], using more sophisticated mathematical techniques and showing how such an approach led to the same phenomena as quantum field theory. It is to be noticed that, in Absorber Theory, the fluctuations of the absorbing atoms play an important role[3,5]. It is also to be noticed that Absorber Theory has different mathematical content from conventional radiation field theory: in going from the one to the other, one has formally to introduce an *approximation* in order to convert the essentially spin-$\frac{1}{2}$ angular momentum algebra of two-level atoms into the boson algebra of the field. The approximation is to assume that the atoms of the absorber are predominantly in their ground states. In numerical terms, this approximation is surely well satisfied!

There have been descriptions of the reaction force within the quantized field formalism, and opinions were divided as to whether the observed phenomena were to be attributed to quantum fluctuations of the field or to quantized radiation reaction, or both[11]. The differences of opinion would appear now to have been resolved and it is generally agreed that the two types of interaction contribute equally to spontaneous emission and level shifts.

In writing classical expressions for radiation reaction it is not essential to work within the Absorber Theory, but it is illuminating to do so, for a reason which it is worth emphasising.

In any theory of radiation, Time's Arrow must appear. It does not do so in classical electromagnetism without arbitrary exclusion of the negative-time solution, nor indeed does it appear in Absorber Theory until some argument concerning the initial state of the universe is inserted. Again, in quantized radiation theory it appears when a particular choice is made for the commutator of non-commuting field components. In the semi-classical theory, therefore, one must expect to find something beyond the classical expression for the reaction force to give a direction to time. One way in which this may be done is by writing in a requirement that the reaction begins only when the atom actually starts to radiate: the time integral of the interaction runs from time zero to time infinity. This, it may be said, begs the question. An alternative requirement, within the context of time-symmetric radiation theory, is that—in a Fourier expansion of the interaction—retarded interactions (those taking place after the beginning of the radiation process) are to be associated with positive frequencies only and advanced interactions (those originating before the onset of radiation) with negative frequencies. This reflects a conclusion reached in an alternative formulation based on correlations of fields, that the interaction we seek is driven by a field imaginary (in the mathematical sense). This, it must be admitted, is unsatisfactory, and it is plausible that this mathematical device hides some underlying physical requirement. We are undoubtedly in deep waters here. The direction of Time's Arrow is a matter of cosmological significance.

Conclusions concerning classical fields

It may be useful to summarize the points we have made:

(i) the semi-classical theory of atom-radiation interactions has a long history of successful interpretation of experiments, especially in the radio-frequency domain;

(ii) laboratory-generated fields need to be supplemented by some further field in order to account for spontaneous emission;

(iii) radiation reaction provides a natural interpretation for the physical basis of this supplementary field;

(iv) though we would not deny the usefulness of fields, nevertheless the fact that fields originate in *sources* should not be overlooked; and

(v) at many points there are significant links with the Absorber Theory of Radiation, and, by further implication, with cosmology.

Quantum optics

The application of the quantum theory of radiation to the optical field has, especially since the advent of the laser, had some remarkable successes which it is not our desire to denigrate, still less to refute. Nor shall we do more than mention a few of the accomplishments of the last thirty years. Our intention is to question the claim that is often made that certain critical experimental tests prove the inadequacy of a classical theory of light as against a quantized field theory. Of course it is inadequate. But that is not the last word.

In our experience the classical theory, despite its great value, not only in interpreting a great variety of resonance experiments in the radio-frequency range, but also in suggesting new techniques and possibilities for the study of matter (pulse experiments in nmr, for example) is successful only insofar as it deals with *stimulated* processes, the absorption and emission of radiation. At frequencies in the optical range spontaneous processes compete strongly with stimulated processes (indeed, the *spontaneous* emission of yellow light from excited sodium atoms is an event many thousands of time more probable than the *absorption* of the radiation from a bright laboratory sodium lamp by those same atoms in their ground states). Hence the need to supplement a theory based on classical (laboratory) fields alone with some further interaction to account for spontaneous emission. We have indicated in previous pages how this might be done, either formally, by postulating the existence of some field based on classical radiation reaction or, more fundamentally, by appealing to interactions with particles in the universe other than the radiating particle itself. The Absorber Theory of Radiation, incorporating quantized matter and time-symmetric electrodynamics accounts for the observed phenomena so far as it has been tested. Moreover, in the direct-action formulation, it has been able to boast a success in explaining observations which conventional quantum theorists label as 'paradoxical'—the phenomenon that correlations between particles may be propagated faster than light (the Einstein-Podolsky-Rosen paradox; the Aspect experiment). In Absorber Theory the interpretation is straightforward[12].

Exponents of quantum optics rarely mention spontaneous emission as the phenomenon *par excellence* where classical fields, without supplementation, fail the test of experiment. In the sixties and seventies the phenomena on which attention was concentrated were concerned with noise and the statistics of photo-electric events. It proved difficult to separate the effects attributable to radiation from the fluctuations inherent in photoelectric emission. Nevertheless, very carefully designed experimentation and the analysis of results revealed the phenomena described as 'photon bunching' and 'photon anti-bunching'. 'Photon bunching' was the term used to describe excess clustering of photoelectric pulses observed when the irradiating light itself fluctuated more than would a classical cosine wave. 'Photon anti-bunching' described a more regular distribution of pulses and was observed experimentally as the response of a detector to the weak resonance fluorescence from a single atom continuously illuminated. The words used to describe the effects pre-judge the issue, whether some basis other than a theory of quantized radiation might have been used to interpret the observations. It seems almost certain that a theory of direct action might have been successful whereby the fluctuations attributed to the radiation field might have been traced to fluctuations in the source atoms and in other particles able to interact with those source atoms. What remains of 'photon bunching' if you accept the description of photons, given at the end of the first section, as 'mathematical entities'?

Fluctuations in the source atoms and in the interactions which drive their emission, as an interpretation of these phenomena, receive support from a more recent, spectacular type of experiment related to the control of noise; the generation of light in what is referred to as 'squeezed states'[13]. A coherent state of the quantized radiation field is subject to fluctuations of phase and amplitude in equal contributions. A 'squeezed state' is one in which, by some means, the phase fluctuations have been reduced at the expense of the amplitude fluctuations, or vice versa. Such situations have been achieved experimentally and are likely to be important in, for example, interferometry of exceedingly high sensitivity. The means by which squeezed states have been realized in the laboratory have been through the nonlinear interaction of laser beams with atoms. Again, a direct-action interpretation would appear to be entirely appropriate.

It will be said that we are nit-picking here, that it is beggarly to deny to quantum field theory the remarkable successes it has achieved in the interpretation of known phenomena and in the opening up of new territory. That is not at all our point of view. We rejoice in these successes and we admire the analytical skills which have been deployed to attain them and the experimental skills which have been brought in to substantiate them. But we deplore any use of language that might suggest that use of the quantized radiation field is *essential* to the interpretation of what is observed. Might not some other way of looking at the phenomena bring further insight? Might it not, at the least, provide an alternative mathematical treatment? One knows that, at the base of the quantum theory of radiation there are unresolved problems which vexed even the founders of the theory to the ends of their lives. One knows that, ultimately, radiation must be a branch of cosmology. The challenges are formidable.

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After this article had been submitted an important paper modifying the cosmological content of the Absorber Theory of Radiation was published by Hoyle, F. and Narlikar, J. V. in *Proc. Roy. Soc. London*, 1993, A442, 469–484. The authors now take account of an event horizon in the universe. The result is that the divergent integrals encountered in conventional QED, as in hoyle and Narlikar's previous work[10], are replaced by finite quantities whose value depends on the Hubble constant. The procedures for renormalization of mas and charge become mathematically acceptable instead of specious. A cloak of respectability then, awaits a theory of radiation prepared to base itself upon a realistic cosmology.

The unscientific side of the ecological movement

P. R. Masani

The ecological movement has fallen short in ignoring the earth's noospheric layer (§ 2) and the fact that the life-destroying interactions stemming from this layer are abnormal (§ 3), and that man is a fallen mammal, Homo peccator (§ 4). The symbiosis of Homo sapiens, faber, peccator (§ 5) and the persistent misappropriation of economic surplus value (§ 6) creates dilemmas for the ecologist (§ 7).

The major noospheric pollutants are the marketing sector of capitalism (§ 8), miseducation (§ 9) and the promotion of idolatry by the judicial system (§ 10). Ecological action, not evasion, on the economic, educational, communications, aesthetic and political fronts is necessary (§ 11 and Postscripts).

Part I. Earth and man

1. *Introduction*

To run the ecological enterprise successfully, it is necessary to understand what the earth is, and since the enterprise is concerned primarily with damage emanating from human folly, and with the remedial engineering that human ingenuity can provide, it is also necessary to understand the nature of man. Thirdly, it is necessary to understand from where the resources required for the enterprise are to come. On all three counts, the ecological movement falls short.

2. *The earth and its layers. The noosphere.*

The biosphere, which 600 million years ago comprised protoplasmic scum on the primordial sea, has by slow orthogenesis produced a layer of plantalia over land and sea, that in turn has sustained an evolution of plant-eating animals, and then carnivores by increasing symbiotic association of independent species. This in turn has supported an evolution of higher mammals, the primates, anthropoids and eventually man, by a process of increasing cerebration and manual dexterity.

Hominization differs, however, from all earlier biological radiations. It has, as it were, superimposed a new layer over the biosphere, by virtue of endowing man with high intelligence, self-consciousness, linguistic prowess and inventiveness. This layer was called the *noosphere* by Father Pierre Teilhard de Chardin (1881–1955) after the Greek word *nous* for mind. He regarded it as a cerebral 'halo' covering the globe. We may think of it as comprising all messages, whether in the mobile

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