COMMENTS

Comments are short papers which criticize or correct papers of other authors previously published in the **Physical Review.** *Each Comment should state clearly to which paper it refers and must be accompanied by a brief abstract. The same publication schedule as for regular articles is followed, and page proofs are sent to authors.*

Comment on "Optical coherence: A convenient fiction"

Julio Gea-Banacloche
Department of Physics, University of Arkansas, Fayetteville, Arkansas 72701
(Received 8 September 1997)

It is argued here that in a large class of lasers there exist mechanisms by which large coherent fields could be generated, and hence there seems to be no compelling reason to regard optical coherence as a "fiction." Some brief comments on the use of a "pointer basis" to resolve statistical mixtures are also presented. [S1050-2947(98)01511-X]

PACS number(s): 42.50.Ct, 42.50.Lc, 03.65.Bz, 11.30.−j

In a recent, thought-provoking article, Mølmer [1] has argued that the usual methods for generating optical fields (in particular, lasers) should not really lead to optical coherences, that is, to fields that have a precise amplitude and phase. He bases his reasoning on the lack of electronic, man-made oscillators at optical frequencies: without an external coherent field to drive the atoms at the optical frequency, he argues, no atomic coherences (nonvanishing atomic dipole moments) could be generated, and therefore the field radiated by the atoms would also have vanishing coherences (i.e., a vanishing expectation value for the amplitude operator a).

The purpose of this Comment is to suggest that, in fact, the way the radiating systems are excited in many lasers—e.g., in a gas laser, by electronic collisions—provides a mechanism that may generate microscopic coherences. The basic classical analogy is that hitting an atom, say, with a fast-moving electron should be similar to hitting a bell: just as the bell will vibrate and generate a sound wave with a precise phase, so would the electronic charge distribution of the atom oscillate with a nonvanishing amplitude and radiate a field with a precise phase.

To see that the analogy carries through when the radiating system is described quantum mechanically, consider, for simplicity, a harmonic oscillator struck at the time t_0 by an impulsive force:

$$H=\frac{1}{2}\,m\omega^2x^2+\frac{1}{2m}\,p^2-F_0\delta(t-t_0)x. \tag{1}$$

The Heisenberg equations of motion are readily solved, with the result that, starting from the ground state,

$$\langle x(t)\rangle=\frac{F_0}{m\omega}\,\sin[\omega(t-t_0)], \tag{2}$$

i.e., we do have a microscopic coherence (nonvanishing dipole moment). Clearly, even though the math is more complicated, the same physics will apply in the case of an atom (or more precisely, an atomic electron) struck by an impulsive force; only, in that case, the nonvanishing dipole moment will have components oscillating at many different atomic transition frequencies, including optical frequencies. These will, in turn, generate microscopic, *coherent* fields at those frequencies.

Of course, in a realistic model of a laser the excitation process would be much more complicated, including fast decay to the lasing levels from the levels initially populated by the electron impact. This fast relaxation is typically nonradiative, i.e., it also involves collisions (e.g., among the atoms themselves), so the general logic carries through, the point being that collisions *can* generate atomic coherences [2]. It is not even necessary to have an impulsive force (i.e., a collision time shorter than an optical period) in order to get a precise phase, although in general, of course, the shorter the collisions the more likely they will be to generate coherences in all frequency scales.

If we assume that most of the spontaneous emission comes from these microscopic dipoles, with well-defined (albeit random) phases, we can show formally how a nonvanishing, macroscopic value for $\langle a\rangle$ could develop. Let the atoms be excited at a rate r, the coupling coefficient of each dipole to the cavity field mode (one-photon Rabi frequency) be g, and the atomic decay rate be γ. At the end of a time $t\gg\gamma$, the amplitude of the cavity field due to spontaneous emission (starting from vacuum) would be of the order of

$$\langle a\rangle\simeq\frac{g}{\gamma}\sum_{i=0}^{rt}e^{i\theta_i}, \tag{3}$$

where the phases θ_i are random, so that, over an ensemble of possible realizations, the average value of $|\langle a\rangle|^2$ would be $rt(g/\gamma)^2$. This, of course, is the same order of magnitude as the average number of photons spontaneously emitted during that time into the cavity mode [3], which means that, in an individual realization of Eq. (3), the microscopic field generated by spontaneous emission would have an amplitude of the order of magnitude of $\sqrt{n}$, and an overall random phase.

If t is of the order of magnitude of the cavity decay rate, the threshold condition is that the number of photons spontaneously emitted into the cavity mode in the time t is of the order of one. So, in a very rough model, we may assume that we start the amplification process with a microscopic coherent field of about 1 photon amplitude. In the linear regime, where the reaction of the fields back on the atomic medium is still negligible, the amplification of the cavity field a is described by the master equation

$$\dot{\rho}=-\alpha(aa^{\dagger}\rho+\rho aa^{\dagger}-2a^{\dagger}\rho a)-\kappa(a^{\dagger}a\rho+\rho a^{\dagger}a-2a\rho a^{\dagger}), \tag{4}$$

where α is the linear gain coefficient, and κ the cavity loss rate. This equation implies that there are no *macroscopic* coherences in the atomic medium as a whole; this is not inconsistent with the earlier argument for the existence of microscopic coherences, it simply means that the phases of the atomic dipoles vary randomly from one atom to the next. Whereas Eq. (4), therefore, does not, by itself, generate a macroscopic coherence, it can and will amplify coherently a coherent microscopic field such as Eq. (3): one gets easily from Eq. (4) that $\langle a(t)\rangle=e^{(\alpha-\kappa)t}\langle a(0)\rangle$. By the time saturation sets in, therefore, one will have a macroscopic-size coherent field amplitude $\langle a(t)\rangle$, with a random phase. (Along these lines, note that experiments have shown [4] how an input coherent field of, on the average, one photon or less is enough to set the phase of the macroscopic field generated by an amplifier to a fair degree, as measured by the visibility of a fringe pattern.)

Clearly, this model has shortcomings: It would be much more instructive to retain the microscopic picture throughout, perhaps in a quantum trajectory simulation that would include all three stages—spontaneous emission, amplified spontaneous emission, and saturation—of the development of the laser field. But it does, I believe, establish the existence of a mechanism whereby a macroscopic optical coherence may be generated in a large class of lasers. I would therefore take issue with the notion that optical coherence is as rare as Mølmer suggests (although I have to agree that, rather remarkably, it may not be easy to establish this rigorously from first principles).

This should not detract from the interest of what I believe is the main point of Mølmer's paper: namely, the fact, beautifully illustrated by his quantum trajectory simulation, that many different *a priori* wave functions for a system may actually yield very similar predictions in the macroscopic limit, and that which way one chooses to resolve a particular density operator—i.e., which states one chooses to ascribe to individual realizations of the ensemble—may ultimately be little more than a matter of convenience. This growing realization [5], along with the (often overlooked) fact that it is simply impossible to determine by a single measurement, no matter how complex, carried out on an individual instance of a system, what the state of that sample instance actually was *prior* to the measurement, leads one to wonder whether there may be any way in which the common presumption that an individual system actually is in *some* quantum state prior to being observed may be made at all meaningful.

There are two ways, I think, in which this notion of an *a priori* wave function may be justified, and neither is free from difficulties. One is the preparation approach—roughly what I have tried to sketch here—basically, to try and figure out what a ''typical'' wave function may be like for a particular system, given an initial state of which we may feel fairly certain (e.g., the vacuum state) and a preparation process that may contain random elements (to be simulated, perhaps, by a stochastic wave-function method). The practical difficulty here is that a detailed simulation may be very complicated and the payoff, as suggested above, may end up being really of only academic interest. There is also a fundamental difficulty, which is the same encountered in quantum measurement theory—namely, how to deal with the quantum nature of the apparatus involved in the state preparation [6].

The other approach is the ''pointer basis'' idea, which is mentioned also in Mølmer's article. Applied to this case, the prescription would be something like, find what the longest-lived states of the system are and adopt them (or something close enough) for the resolution of the density operator. While I believe this idea has merit, and I have attempted to use it to look at the question of the field generated by a laser in [7], I do not expect this point of view to be readily embraced by even a majority of the physics community. Mølmer, for instance, clearly disagrees with one of the basic tenets—namely, that the overlap between two states, as measured by their inner product, may be used as a good measure of how similar or different they are. Without such a measure, however, one cannot decide on the question of a state's lifetime. Mølmer suggests that ''measures of identity and/or difference other than the inner product are called for,'' but he does not suggest a specific criterion, nor do I believe that any criterion he might suggest would be accepted any more readily by the community at large.

[1] K. Mølmer, Phys. Rev. A **55**, 3195 (1997).

[2] There is a large body of literature, both experimental and theoretical, on collision-induced coherences in atoms, and some of it is almost certain to be relevant to this discussion. See, for a recent theoretical treatment and many references, G. Grynberg and P. R. Berman, Phys. Rev. A **39**, 4016 (1989).

[3] See, e.g., M. Sargent III, M. O. Scully, and W. E. Lamb, Jr., *Laser Physics* (Addison-Wesley, Reading, MA, 1974), Chap. 17.

[4] R. C. Swanson, P. R. Battle, and J. L. Carlsten, Phys. Rev. Lett. **67**, 38 (1991).

[5] See, e.g., J. I. Cirac, C. Gardiner, M. Narachewski, and P. Zoller, Phys. Rev. A **54**, R3714 (1996); also J. Javanainen and S. M. Yoo, Phys. Rev. Lett. **76**, 161 (1996).

[6] For instance, in the model I have presented here, a critical assumption is that the electron current in the discharge tube is treated as, essentially, a stream of classical particles. If, instead, the individual electrons were quantized, one would have

to deal with the possibility of entanglement between the electrons and the atoms (as well as with other issues, such as the spreading of the electron wave packet). Entanglement, in particular, would destroy the atomic coherence if the energy of the incoming electron is more sharply defined than the few eV of a typical optical transition. It can be argued that this would not generally be the case in a high-voltage discharge tube, but this shows the kinds of difficulties a first-principles calculation would have to face.

[7] J. Gea-Banacloche, Found. Phys. **28**, 531 (1998).