Reply to “Comment on “Some implications of the quantum nature of laser fields for quantum computations” ”

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We point out several superficialities in Itano’s comment (quant-ph/0211165).

Although the recent Comment by Itano [1] is directed at two papers by J. Gea-Banacloche [2], it also calls into question our paper [3]. Here we address the latter criticisms, and show that the arguments in Itano’s comment are superficial and do not affect the correctness nor conclusions of our analysis.

Itano claims that a laser field initially in a coherent state does not become entangled with an atom it is interacting with, in contrast to the conclusion we reached in [3], and that all the decoherence effects discussed there can in fact be attributed to spontaneous emission. Three arguments are given for this conclusion:

1. The formalism that we employed in [3] is “inappropriate” for the setting of free space, since the field is not confined by a cavity.

2. Mollow [4] showed that by applying an appropriate unitary transformation the Hamiltonian can be transformed into one that describes the interaction of the atom with a classical field and the vacuum. Clearly, the classical field will not become entangled with the atom, so all entanglement can only be with the vacuum.

3. In free space, the atom radiates a dipole field and coherent forward scattering, “which do not modify the incident field”.

Our responses are

1. Ref. [5] discusses how one may quantize the electromagnetic field in terms of freely propagating modes, not confined by any cavity. That is the formalism we used, with the propagating laser pulse being one of those modes. Now it is true one has to be careful when describing the interaction of such a mode with an atom, as pointed out in the paper by Silverfarb and Deutsch [6], with which we agree. Although Itano refers to the fact that Silverfarb and Deutsch have “independently reached similar conclusions,” to those in his comment [1], this actually refers to another issue: Refer to the second paragraph of Section II in [6]: “This approach was taken by van Enk and Kimble and also by Gea-Banacloche ...” whose ... “analysis led to an effective single temporal mode theory. Though their conclusions are correct (our emphasis), one must take great care to understand the regimes under which this formalism is applicable,” which we did indeed do in Ref. [3]. The subject of our paper was to assess the amount of decoherence due to the atom-laser field entanglement only, while leaving out all other decoherence effects, in particular spontaneous emission into modes that are initially empty. We of course agree that if spontaneous emission is included, a single-mode model cannot be correct, as explicitly demonstrated in [6]. The result of [3] is that the decoherence effect due to stimulated emission into the laser mode is much smaller, in general, than decoherence due to spontaneous emission, but not zero. Note that in Section III A of [6] it is concluded that “decay due to entanglement with the laser modes is small compared to decay due to spontaneous emission...” but this entanglement is not zero, exactly as concluded and calculated explicitly in [3], but in disagreement with Itano’s statements, who claims the decoherence due to laser-atom entanglement is zero.

2. The “vacuum” in the Mollow picture is not the standard vacuum. Having initially performed Mollow’s unitary transformation $U$, one has to apply the inverse operation $U^\dagger$ to get back to the correct physical picture. In particular, if an atom emits a photon into a mode that was occupied prior to the initial transformation $U$, the “one-photon state” will be transformed by $U^\dagger$ back to a state that is close to, but not quite equal to, a coherent state. Thus, the atom becomes entangled with the laser field by stimulated emission into the laser mode, exactly as we concluded in [3].

3. In two previous related papers [7], not mentioned by the Comment, we studied how quantum-statistical properties of an incident field are modified by its interaction with a single atom. We used a well-known expression for the total electric field in the Heisenberg picture, namely $\vec{E} = \vec{E}_{\text{free}} + \vec{E}_{\text{source}}$. The “source” field is a dipole field (in the far field). If one identifies that field with spontaneous emission (which Itano seems to do) and the “free” field with the incident field, one would indeed conclude that the incident field is never ever changed (there is only free evolution). While this may be formally
true, it is physically irrelevant, since only the total field \( \vec{E} \) is relevant subsequent to the atom-field interaction. That Itano’s conclusion is odd, to say the least, can be seen from the fact that it would hold regardless of the state of the incident field, not just for coherent states, but for Fock states as well. What Itano overlooks is that the incident laser field will contain dipole waves as well. Subsequent to the interaction, the dipole waves in the incident field cannot be distinguished from the dipole waves emitted by the atom. For example, if an atom scatters a photon from the incident beam into other modes, or if an initially excited atom deposits a photon into the laser mode, there are unavoidable imprints of these processes left in the total forward propagating field \( \vec{E} \), since after all energy is conserved.

In short, while we agree that one has to take great care applying a single-mode model to the description of the interaction of an atom with a laser field in free space, we do not agree with any of the arguments put forward by Itano that purportedly show that the laser-atom entanglement is zero.

[1] W. Itano, quant-ph/0211165.
[2] J. Gea-Banacloche, Phys. Rev. A 65, 022308 (2002); Phys. Rev. Lett. 89, 217901. See also quant-ph/0212027.
[3] S.J. van Enk and H.J. Kimble, Quantum Inf. and Comp. 2, 1 (2002).
[4] B.R. Mollow, Phys. Rev. A 12, 1919 (1975).
[5] K.J. Blow, R. Loudon, S.J. Phoenix, and T.J. Shepherd, Phys. Rev. A 42, 4102 (1990).
[6] A. Silverfarb and I.H. Deutsch, quant-ph/0210056
[7] S.J. van Enk and H.J. Kimble, Phys. Rev. A 63, 023809 (2001); ibidem 61, 051802 (2000).