Reply I to "Comment on 'Some implications of the quantum nature of laser fields for quantum computations' "

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We show that Itano's arguments confirm our conclusion, that entanglement of the atom with the laser field contributes a small but nonzero amount to the total decoherence of an atom in a laser field. This small effect scales as $1/\bar{n}$ with $\bar{n}$ the average number of photons in the laser pulse.

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Although the Comment by Itano [1] is directed at the two papers by Gea-Banacloche [2], it also calls our paper [3] into question. Here we address the latter's criticisms, and show that the arguments in Itano's Comment do not contradict but in fact confirm the 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 Ref. [3], and that all the decoherence effects discussed there can in fact be attributed to spontaneous emission. This is mainly based on the following argument: Mollow [4] showed that by applying an appropriate unitary transformation U, the atom-field Hamiltonian can be transformed into the one that describes the interaction of the atom with a classical field and the quantum vacuum. Clearly, the classical field will not become entangled with the atom, so decoherence can only be due to the interaction with the vacuum.

We now point out that this argument tells only half the story. The "vacuum" in the Mollow's 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 $U^\dagger$ to a state that is close to, but not quite equal to, the original coherent state. If $\bar{n}$ is the average number of photons in the initial coherent state, the difference between the two states is of order $1/\bar{n}$. Thus, the atom becomes entangled with the laser field by emission into the laser mode, exactly as we concluded in Ref. [3].

In addition we respond to some side issues: When referring to the "beam-area paradox," Itano misrepresents our paper by (again) telling only half the story. 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 we explicitly left out spontaneous emission into modes that are initially empty. Thus, while the total decoherence is independent of the beam area (and this is indeed most easily seen by employing the Mollow's transformation) a smaller focusing area leads to more decoherence due to emission into the laser mode [according to our Eq. (31). The reason is simply that the overlap of the laser field with a dipole wave tends to increase with stronger focusing [5]. Thus, with stronger focusing the atom scatters more light into initially populated modes and less into initially empty modes. Decoherence due to the former is attributed, in our language, to atom-field entanglement.

We of course agree that if spontaneous emission is included, a single-mode model is incorrect, as explicitly demonstrated in Ref. [6]. Itano probably refers to this when saying that Silberfarb and Deutsch reach similar conclusions. However, concerning the issue at debate we note that Sec. III A of Ref. [6] concludes 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 in Ref. [3], but in disagreement with Itano's statements, who claims that the decoherence due to laser-atom entanglement is *zero*.

In short, we find that Itano raises some good points, but his arguments are not fully developed. In particular, they do not refute our conclusions but rather confirm them.

[1] W. Itano, preceding paper, Phys. Rev. A **68**, 046301 (2003).
[2] J. Gea-Banacloche, Phys. Rev. A **65**, 022308 (2002); Phys. Rev. Lett. **89**, 217901 (2002); see also quant-ph/0212027.
[3] S.J. van Enk and H.J. Kimble, Quantum Inf. Comput. **2**, 1 (2002).
[4] B.R. Mollow, Phys. Rev. A **12**, 1919 (1975).
[5] S.J. van Enk and H.J. Kimble, Phys. Rev. A **63**, 023809 (2001); **61**, 051802 (2000); S.J. van Enk, e-print quant-ph/0307216.
[6] A. Silverfarb and I.H. Deutsch, Phys. Rev. A **68**, 013817 (2003).

