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Reply to "Comment on 'Quantum Zeno effect' "

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Various interpretations of quantum mechanics are valid insofar as they predict the same experimental results. Some invoke "wave-function collapse" and some do not. An interpretation based on the collapse postulate provides a simple explanation for a recent experimental demonstration of the quantum Zeno effect [Itano *et al.*, Phys. Rev. A 41, 2295 (1990)], but other interpretations are also valid.

The theory of quantum mechanics has the unusual property that, while there is general agreement on the experimental consequences, there is endless debate on matters of interpretation. The preceding Comment by Ballentine[1] on our article[2] illustrates this point.

The choice among interpretations that yield identical predictions, including the standard Copenhagen interpretation, the "statistical" or "ensemble" interpretation favored by Ballentine,[3] or even Everett's "relative-states" or "many-worlds" interpretation,[4] would seem to be a matter of personal taste. Ballentine states that "collapse of the wave function" is not necessary to quantum mechanics. We agree. However, we feel that the explanation given in our article, which invokes von Neumann's "collapse" postulate, is useful for giving a simple explanation of our experiment. Other situations may require a more elaborate treatment. One such case is the limit in which the optical "measurement" pulses are too weak to completely "collapse" the wave function. Peres and Ron[5] have carried out a calculation for this case.

We agree that the optical pulses perturb the atom, and we do not state otherwise in our article. However, we disagree with Ballentine's statement that the inhibition of the excitation is due to a strong perturbation *rather* than to a collapse of the wave function caused by measurement. We regard both statements as valid, under different interpretations of quantum mechanics.

Ballentine criticizes the phrase "wave-function collapse due to a null measurement," as being misleading. We used this term in the sense in which it was used by Porrati and Putterman,[6] to mean that the nonemission of a photon during (or immediately subsequent to) the optical pulse is correlated with the atom being in the metastable state. We did not mean to imply that the optical pulses did not perturb the atom.

Ballentine objects to our use of the word "measurement" and quotes the *Oxford English Dictionary* to support his case. Dictionaries contain definitions of words like "energy," "force," or "work" that do not correspond to their meanings in physics. Therefore, one has to look at the way in which the words are used by physicists. It *is* true that the "measurement" pulses did not actually yield a detectable signal. Our usage of the word "measurement" in this case seems to be the same as that of Carmichael *et al.*[7] in their discussion of the theory of the detection of photons from resonance fluorescence. (This situation is very similar to that of an atom subjected to a measurement pulse.)

"The detector is not the agent *causing* state reduction. The atom collapses to its ground state due to its *irreversible* decay into the vacuum; the collapses proceed at an average rate given by the inverse atomic lifetime, quite indifferent to the successful or unsuccessful recording of the emitted photons." (Ref. 7, p. 1202.)

"... the source is an open system that loses energy *irreversibly* to the vacuum. The irreversibility effectively performs a continuous quantum measurement, without the need for a conscious observer to record the emitted photons." (Ref. 7, p. 1215.)

Ballentine carries out a simplified interpretation of our experiment. He calculates that the probability that each of a sequence of n optical "measurement" pulses results in the emission of a photon, leaving an atom in the ground state after the nth pulse, is $[\cos(\pi/2n)]^{2n}$. This calculation is correct, but is not particularly useful for comparison with our observable. Our experiment measures the total probability that an atom is left in the ground state after the nth pulse, regardless of whether or not each optical pulse resulted in the emission of a photon. This probability is, in our notation, $P_1(T)=1-P_2(T)=\frac{1}{2}[1+\cos^n(\pi/n)]$. This result comes from Eq. (7) of Ref. 2. (Here we neglect the duration of the optical pulses, as does Ballentine.) The two probabilities are not identical, because the rf field can drive the atom to the metastable state in one interval and return it to the ground state in a later interval. [Ballentine[1] states in his Ref. 10 that his method will also yield the proper value of $P_1(T)$, although he does not show this explicitly.]

In summary, quantum mechanics can be interpreted in different ways. In this case, interpretations with and without the collapse postulate correctly predict the experimental data. Therefore, the experiment neither verifies nor falsifies the notion of "wave-function collapse."

[1]L. E. Ballentine, preceding Comment, Phys. Rev. **43**, 5165 (1991).
[2]W. M. Itano, D. J. Heinzen, J. J. Bollinger, and D. J. Wineland, Phys. Rev. A **41**, 2295 (1990).
[3]L. E. Ballentine, Rev. Mod. Phys. **42**, 358 (1970).
[4]H. Everett, Rev. Mod. Phys. **29**, 454 (1957).
[5]A. Peres and A. Ron, Phys. Rev. A **42**, 5720 (1990).
[6]M. Porrati and S. Putterman, Phys. Rev. A **36**, 929 (1987).
[7]H. J. Carmichael, S. S. Singh, R. Vyas, and P. R. Rice, Phys. Rev. A **39**, 1200 (1989).