High-Efficiency Quantum Interrogation Measurements via the Quantum Zeno Effect

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The phenomenon of quantum interrogation allows one to optically detect the presence of an absorbing object, without the measuring light interacting with it. In an application of the quantum Zeno effect, the object inhibits the otherwise coherent evolution of the light, such that the probability that an interrogating photon is absorbed can in principle be arbitrarily small. We have implemented this technique, achieving efficiencies of up to 73%, and consequently exceeding the 50% theoretical maximum of the original "interaction-free" measurement proposal. We have also predicted and experimentally verified a previously unsuspected dependence on loss.

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"Negative result" measurements were discussed by Renninger [1] and later by Dicke [2], who analyzed the change in an atom's wave function by the *nonscattering* of a photon from it. In 1993 Elitzur and Vaidman (EV) showed that the wave-particle duality of light could allow "interaction-free" quantum interrogation of classical objects, in which the presence of a nontransmitting object is ascertained seemingly without interacting with it [3], i.e., with no photon absorbed or scattered by the object. In the basic EV technique, an interferometer is aligned to give complete destructive interference in one output port—the "dark" output—in the absence of an object. The presence of an opaque object in one arm of the interferometer eliminates the possibility of interference so that a photon may now be detected in this output. If the object is completely nontransmitting, any photon detected in the dark output port must have come from the path *not* containing the object. Hence, the measurements were deemed interaction-free, though we stress that this term is sensible only for objects that completely block the beam. For measurements on partially transmitting (and quantum) objects, we suggest the more general terminology "quantum interrogation." In any event, there is necessarily a coupling between light and object (formally describable by some interaction Hamiltonian)—somewhat paradoxically, in the high-efficiency schemes discussed below, it is crucial that the *possibility* of an interaction exist, in order to reduce the probability that such an interaction actually occurs.

The EV gedanken experiment has been realized using true single-photon states [4]; with a classical light beam attenuated to the single-photon level [5]; and in neutron interferometry [6]. It has even been employed to investigate the possibility of performing "absorption-free" imaging [7]. The EV technique suffers two serious drawbacks, however. First, the measurement result is ambiguous at least half of the time—a photon may be detected in the nondark output port whether or not there is an object. Second, at most half of the measurements are interaction-free [4,7]. Following Elitzur and Vaidman [3], we define a figure of merit $\eta = P(\mathrm{QI})/[P(\mathrm{QI}) + P(\mathrm{abs})]$ to characterize the "efficiency" of a given scheme, where $P(\mathrm{QI})$ is the probability that the photon is detected in the otherwise dark port, and $P(\mathrm{abs})$ is the probability that the object absorbs or scatters the photon. Physically, η is the *fraction* of measurements that are interaction-free. The maximum achievable efficiency in the EV scheme, obtained by adjusting the reflectivities of the interferometer beam splitters, is $\eta = 50\%$ [3,4,7].

It was proposed that one could circumvent these limitations by using a hybrid scheme [4], combining the interferometric ideas of EV and incorporating an optical version of the *quantum Zeno effect* [8], in which a weak, repeated measurement inhibits the otherwise coherent evolution of the interrogating photon. Our specific embodiment of the Zeno effect is based on an inhibited polarization rotation [9], although the only generic requirement is a weakly coupled multilevel system. A photon with horizontal $(\mathbf{H})$ polarization is directed through a series of N polarization rotators (e.g., optically active elements), each of which rotates the polarization by $\Delta\theta \equiv \pi/2N$. The net effect of the entire stepwise quantum evolution is to rotate the photon's polarization to vertical $(\mathbf{V})$. We may inhibit this evolution if at each stage we make a measurement of the polarization in the $\mathbf{H}/\mathbf{V}$ basis, e.g., by inserting a horizontal polarizer after each rotator. Since the probability of being transmitted through each polarizer is just $\cos^2\Delta\theta$, the probability $P(\mathrm{QI})$ of being transmitted through all N of them is simply $\cos^{2N}(\Delta\theta) \approx 1 - \pi^2/4N$, and the complementary probability of absorption is $P(\mathrm{abs}) \approx \pi^2/4N$. Thus, increasing the number of cycles leads to an arbitrarily small probability that the photon is ever absorbed.

Obviously the Zeno phenomenon as described is of limited use, because it requires polarizing objects. Figure 1 shows the basic concept which allows quantum interrogation of *any* nontransmitting object. A single photon is made to circulate N times through the setup, before it is removed and its polarization analyzed. As in the example above, the photon, initially $\mathbf{H}$ polarized, is rotated by $\Delta\theta = \pi/2N$ on each cycle, so that after N cycles the

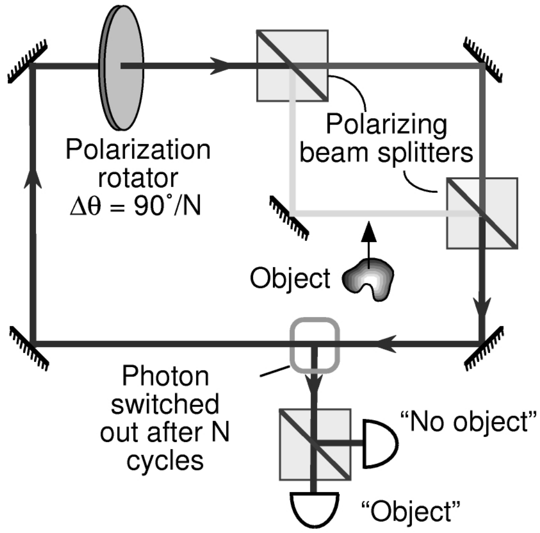

FIG. 1. Simple schematic of a hybrid scheme to allow high-efficiency quantum interrogation of the presence of an opaque object. With no object, the initial horizontal polarization of the interrogating photon is rotated stepwise to vertical. The presence of an object in the **V** arm inhibits this evolution via the optical quantum Zeno effect [9], so that the final polarization after N cycles unambiguously indicates the presence or absence of the object: **V** polarization → no object; **H** polarization → object.

photon is found to have **V** polarization. This rotation is unaffected by the polarization interferometer (consisting of two polarizing beam splitters, which ideally transmit all **H**-polarized and reflect all **V**-polarized light, and two identical-length arms), which simply separates the light into its **H** and **V** components and adds them back in phase. If there is an object in the vertical arm of the interferometer, however, only the **H** component of the light is passed; i.e., each *non*absorption by the object [with probability $\cos^2\Delta\theta$] projects the wave function back into its initial state. Hence, after N cycles, either the photon will still have **H** polarization [with probability $P(\mathrm{QI})$], unambiguously indicating the presence of the object, or the object will have absorbed the photon [probability $P(\mathrm{abs})$]. By going to higher N, $P(\mathrm{abs})$ can, in principle, be made arbitrarily small. In the absence of losses or other nonidealities, $\eta = P(\mathrm{QI})$, so that $\eta \to 1$ as $N \to \infty$.

Demonstrating this phenomenon in an actual experiment required several modifications (see Fig. 2). A horizontally polarized laser pulse was coupled into the system by a highly reflective mirror. The light was attenuated so that the average photon number per pulse after the mirror was between 0.1 and 0.3. The photon then bounced between this recycling mirror and one of the mirrors making up a polarization Michelson interferometer. At each cycle a wave plate rotated the polarization by $\Delta\theta$. After the desired number of cycles N, the photon was switched out of the system by applying a high-voltage pulse to a Pockels cell in each interferometer arm, thereby rotating the polarization of the photon by 90°, so that it exited via the other port of the polarizing beam splitter. The exiting photon was then analyzed by an adjustable polarizer and single-photon detector. With no object, the polarization was found to be essentially horizontal, indicating that the stepwise rotation of polarization had taken place (remember, the final polarization is 90° rotated by the Pockels cell). With the object in the vertical-polarization arm of the interferometer, this evolution was inhibited, and a photon exiting the system was vertically polarized, a quantum interrogation of the presence of the object [10].

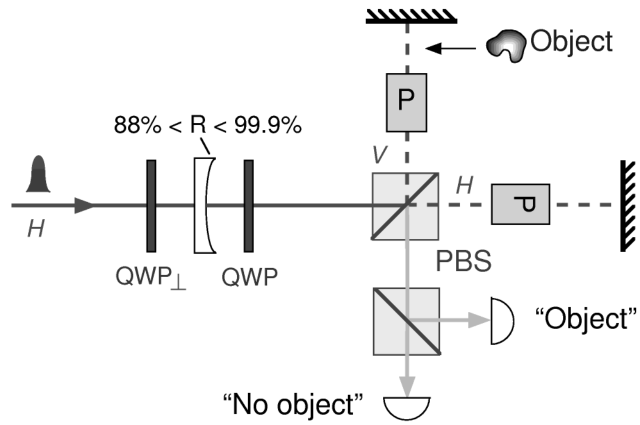

FIG. 2. Experimental system to demonstrate high-efficiency quantum interrogation. Photons from a pulsed laser at 670 nm are coupled into the recycling system via a high-reflectivity recycling mirror (initially flat, later curved; see Fig. 3). A double pass through the quarter wave plate (QWP) served to rotate the polarization by a fixed amount during each cycle; an extra wave plate ($\mathrm{QWP}_\perp$) in the entrance beam was used to compensate for the initial pass. On each cycle the photon passed through a polarization interferometer [with a polarizing beam splitter (PBS)]; to fine-tune the interferometer phase, one mirror was mounted on a piezoelectric "bimorph." The Pockels cells (P) were used to switch the photons out after a desired number of cycles—a ~3 kV pulse was applied, which after the double pass rotated the polarization of the photon by 90°, so that it exited via the other port of the PBS. The exiting photon was then analyzed by the adjustable polarizer and single-photon detector [EG&G No. SPCM-AQ-141, preceded by an interference filter (10 nm FWHM, centered at 670 nm) to reduce background]. The final polarization of the detected photon indicates the presence (**V** polarized) or absence (**H** polarized) of an object in the reflected arm of the interferometer. (Not shown: an active feedback helium neon laser which ran below the plane of the 670 nm light, to stabilize the interferometer.)

A number of intermediate configurations were investigated before arriving at the arrangement described above [11]. With these the *feasibility* of quantum interrogation with η up to 85% was inferred (for a hypothetically lossless system)—there was no way to directly measure the amount of light absorbed by the object. In the present experiment, we made a *direct* measurement of the probability that a photon took the object path, by applying a constant voltage to the Pockels cell in that path, thereby directing these photons to the single-photon detector at each cycle. With the dc voltage applied, photons exiting with **H** polarization correspond to $P(\text{abs})$, while those with **V** polarization (which exit only after N cycles) correspond to $P(\text{QI})$. [The rates corresponding to $P(\text{QI})$ were similar whether using the dc-biased Pockels cell as the object, or physically blocking that arm of the interferometer.] Rather unexpectedly, the efficiencies determined in this fashion were significantly lower than both the theoretical predictions and the previous inferred measurements, which agreed well with each other. The reason is that the effects of *loss* in the system were normalized out in the previous measurements [11].

That loss should reduce the actual efficiencies was somewhat surprising, since losing a photon from the system seems equivalent to never sending it in initially. This line of reasoning is faulty: A photon contributing to $P(\text{QI})$ must necessarily remain in the system for all N cycles, thus experiencing any loss N times; in contrast, a photon contributing to $P(\text{abs})$ could be absorbed on any cycle, hence it remains in the system on average less than N cycles, and sees less loss than a photon contributing to $P(\text{QI})$. The net effect is that, whereas $\eta \rightarrow 1$ for a large number of lossless cycles, in the presence of loss η reaches a maximum value less than one before falling again toward zero [12]. This places a strong constraint on the achievable efficiencies in any real system.

Figure 3 shows the experimental verification of this phenomenon, as well as the modified theoretical predictions, which are in good agreement. Despite the efficiency reduction due to loss, we were able to observe η's of up to 74.4% $\pm$ 1.2%. Also shown in Fig. 3 are several representative measurements of the "noise" of our quantum interrogation system, from events in which an object was indicated (i.e., photons were detected with vertical polarization) even though none was actually present. The main causes were imperfections of the optical elements and interferometer instability, despite active stabilization.

Because the same photon detector was used to determine both $P(\text{QI})$ and $P(\text{abs})$ in our measurements, the detector efficiency factors out of the calculation for η. When our highest-observed value of η is corrected for our finite detection efficiencies [13], we arrive at an adjusted η of 53.1% $\pm$ 1.6%, where we have included the effects of both the detector efficiency (65%) and the 10-nm filter (60% transmission) used to reduce background. Because this value of η is only marginally above the 50% threshold of the original EV scheme, we also took one set of data in which the 10-nm filter was removed. Our measured η was 72.3% $\pm$ 1.1%, implying a raw efficiency of 62.9% $\pm$ 1.3%: In measurements with the opaque object, $\sim 2/3$ of the photons performed an interaction-free measurement, and $\sim 1/3$ did not [10]; i.e., the object's presence can be unambiguously determined while absorbing only "1/3 of a photon". This is, to our knowledge, the first practical utilization of the quantum Zeno effect.

A wholly different method of quantum interrogation, relying on disrupting the resonance condition of a high-finesse cavity (and hence called "resonance interaction-free measurement"), has been proposed [14] and recently demonstrated [15], with efficiencies similar to those reported here. If both cavity mirrors have reflectivity R, a narrow bandwidth photon incident on the empty cavity can have a near-unity probability of transmission; i.e., in principle, a detector observing the reflection from the entrance mirror to the cavity will never fire. An object in the cavity will prevent the resonance condition (this can be thought of as an impedance mismatch), so the reflected-mode detector will detect the photon with probability $P(\text{QI}) = R$, while the object will absorb the photon with probability $1 - R$. The efficiency of this scheme (R, in the ideal case) can thus exceed the EV 50% threshold, like the method based on the Zeno effect. The two techniques have very different characteristics, however. For example, while the Zeno technique employs broadband photon wave packets, the resonance methods require a very narrow frequency spectrum for the interrogating photons. Because of the pulsed nature of the Zeno effect, the duration of the experiment is precisely fixed (to N cycles); the duration with the cavity method is less well defined, determined by the ringdown time of the cavity. Conversely, it is relatively easy to allow photons to leak out of a cavity, whereas actively switching them as in our scheme is experimentally more challenging. Finally, as presented here, both techniques require interferometric stability; however, this is not strictly necessary for

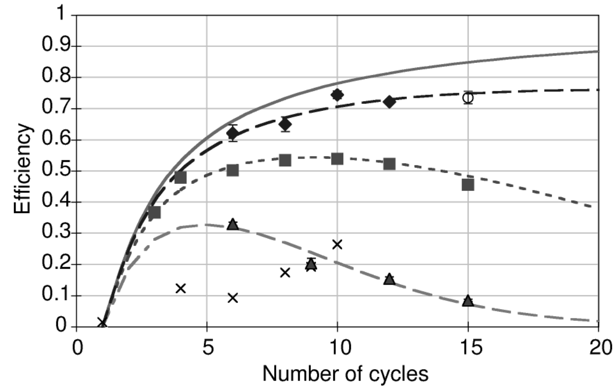

FIG. 3. Efficiency versus number of cycles N for several system configurations. The curves are theoretical predictions based on the measured losses for each configuration. The triangles and the dotted-dashed curve correspond to a lossy nonswitching system in which the photons experienced 8% loss/cycle due to the input coupler, and leaked out through a flat 88% reflective output coupler. The squares and dotted curve correspond to the system in Fig. 2, with a somewhat lossy Pockels cell in the no-object arm ($T = 95.1\%$) and a flat recycling mirror ($R = 96.2\%$). The diamonds and the dashed curve correspond to a better Pockels cell ($T = 97.7\%$) and a curved recycling mirror ($R = 97.4\%$), and the circle corresponds to a higher reflectivity ($R = 99.4\%$) curved mirror. The solid curve is the prediction for a lossless system. Several representative measurements of the noise in our quantum interrogation process are also shown (crosses).

the Zeno method if one has a polarizing object, e.g., a polarization-selective atomic transition.

Achieving higher efficiencies with these techniques will require increasing the working number of cycles N. However, the performance of the system becomes increasingly more sensitive to optical imperfections and to interferometer instability. The effect of loss is also multiplied. We believe that with sufficient engineering these problems could be reduced, allowing operation at up to $O(100)$ cycles or higher, giving efficiencies $>93\%$ [16]. Finally, *cross talk* in the polarizing beam splitter (i.e., not all horizontal polarized light is transmitted, and not all vertical polarized light is reflected, about $\sim 1\%$ in our present system) must be kept to a minimum. In particular, we observed spurious interference effects when the reflection probability $[\sin^2(\pi/2N)]$ becomes comparable to the cross talk. Use of birefringent material polarizers, whose cross talk figures are $\sim 10^{-5}$, may mitigate this problem.

If the efficiencies can be improved as discussed above, one can envision using the methods to examine quantum mechanical objects, such as an atom or ion, one of whose states couples to the interrogating light ("object"), and another of whose states does not couple ("no object"). In the simplest situation we can determine which state the system is in with a greatly reduced probability of exciting it out of that state. Such a process might be called "absorption-free spectroscopy," and could be useful for studying photosensitive systems. More interestingly, when the quantum system is in a superposition of the two states, the light becomes *entangled* with the quantum system [3,17–19]. Such an effect may have use as a quantum "wire," e.g., as an interface for connecting together two quantum computers [20]. Finally, in the limit as $\eta \to 1$, these techniques of quantum interrogation will function even if there are several photons (or an *average* of several photons, as in a weak coherent state). It should then be possible to produce Schrödinger-catlike states $\alpha|VVV\ldots\rangle + \beta|HHH\ldots\rangle$, where $|VVV\ldots\rangle$ ($|HHH\ldots\rangle$) represents several photons with vertical (horizontal) polarization [17]. Such states would have great interest for studying the classical-quantum boundary and the phenomenon of decoherence.

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[12] As before, $\eta = P(\mathrm{QI})/[P(\mathrm{QI}) + P(\mathrm{abs})]$, but now we have

$$P(\mathrm{QI}) = (T_{\mathrm{empty}} \cos^2\Delta\theta)^N (T_{\mathrm{rec}})^{N-1}$$

$$P(\mathrm{abs}) = \frac{T_{\mathrm{obj}} \sin^2\Delta\theta[1 - (T_{\mathrm{empty}} T_{\mathrm{rec}} \cos^2 \Delta\theta)^N]}{(1 - T_{\mathrm{empty}} T_{\mathrm{rec}} \cos^2 \Delta\theta)},$$

where N is the number of cycles, $\Delta\theta = \pi/2N$, and T_{empty}, T_{obj}, and T_{rec} are, respectively, the single-cycle transmission probabilities for the empty interferometer arm, the arm with the object, and the recycling arm ($\equiv T_{\mathrm{QWP}}^2 R_{\mathrm{mirror}}$, with R_{mirror} the recycling mirror reflectivity). See also J.-S. Jang, Phys. Rev. A **59**, 2322 (1999).
[13] If the observed efficiency is η_{obs}, and the net detection efficiency is ϵ, then the adjusted η is given by $\eta_{\mathrm{obs}}\epsilon/[1 - \eta_{\mathrm{obs}}(1 - \epsilon)]$.
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[16] This estimate assumes a single-pass Pockel-cell transmission of 99.5%, recycling mirror reflectivity of 99.9%, and reflection losses of 0.05% on the QWP and PBS surfaces (all obtainable specifications with current technology). Modern stabilization techniques for high-finesse optical cavities routinely achieve >1000 round-trips. The resulting maximum intrinsic efficiency of 94.5% (at $N = 107$) is reduced to 93.2% for detector efficiencies of 80% [13].
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