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Interaction-Free Measurement

Paul Kwiat, Harald Weinfurter, Thomas Herzog, and Anton Zeilinger
Institut für Experimentalphysik, Universität Innsbruck, Technikerstrasse 25, 6020 Innsbruck, Austria

Mark A. Kasevich
Department of Physics, Stanford University, Stanford, California 94305
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We show that one can ascertain the presence of an object in some sense without interacting with it. One repeatedly, but weakly, tests for the presence of the object, which would inhibit an otherwise coherent evolution of the interrogating photon. The fraction of "interaction-free" measurements can be arbitrarily close to 1. Using single photons in a Michelson interferometer, we have performed a preliminary demonstration of some of these ideas.

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One of the commonly cited differences between classical and quantum physics is that in the former the disturbance of the system under observation can be made arbitrarily small, while in the latter the measurement process in general disturbs the system. Yet, Renninger used the notion of a "negative-result measurement" to describe the *nonobservance* of a particular result as a measurement of a quantum system, seemingly without disturbing it [1]. The concept of an "interaction-free" quantum measurement was then considered by Dicke, who analyzed the change of an atom's wave function effected by the *nonscattering* of a photon from it [2]. Elitzur and Vaidman (EV) extended these ideas, so that the presence of an object modified the *interference* of a photon, even though the photon and the object need not have interacted [3]. The maximum attainable efficiency in the EV scheme is 50%.

We have discovered an improved method where the fraction of interaction-free measurements can be arbitrarily close to 1 [4]. In the new version, which may be viewed as an application of a discrete form of the quantum Zeno effect, one coherently repeats the interrogation of the region that might contain the object. As an intermediate step we have used the single-photon states available from spontaneous parametric down-conversion to experimentally demonstrate the principle of an interaction-free measurement.

The initial proposal of EV employs an interferometer aligned so that an incident photon (or any other interfering particle) will with certainty exit via a given output port, the "bright" port. Thus, in the absence of any object within the interferometer, the photon will *never* be detected in the "dark" output port. The presence of an absorbing (or, more generally, nontransmitting) object in one of the arms changes completely the possible outcomes by destroying the interference. For a beam splitter of reflectivity R (and transmissivity $T = 1 - R$), any incident photon will encounter the object with probability R and be absorbed. There is a probability R^2 that the photon will still exit to the bright port; since this yields no information, the experiment should be repeated (either with the same photon or with a new one). However, there is also a probability RT that the photon will exit to the dark output port. Detecting this photon, one can conclude that an object was certainly in one arm of the interferometer, even though the photon could not have interacted with it. To make the argument more dramatic, EV proposed that the object could be an ultrasensitive bomb, triggered by the absorption of a single photon.

The complementarity of a single quantum is essential for the above method: In the absence of the object, it is the wavelike nature of the incident light which allows us to establish, through destructive interference, a condition in which the photon never uses the dark output;

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in the presence of the object, it is the indivisibility of the quantum which enforces the mutual exclusivity of the possible outcomes.

For a lossless system, the fraction η of measurements that can be interaction free is given by

$$\eta = \frac{P(\text{det})}{P(\text{det}) + P(\text{abs})}, \tag{1}$$

where $P(\text{det})$ is the probability of detecting the presence of the object, and $P(\text{abs})$ is the probability that the photon is absorbed by the object. In the case considered above, $\eta = RT/(RT + R) = (1 - R)/(2 - R)$, which tends to the upper limit of 50%. We stress that from the viewpoint of a single event, a successful measurement is *completely* interaction-free (in the sense that the photon is not absorbed by a perfectly absorbing object), even though the likelihood of such a measurement is only 1/2.

Here we present a different method that in principle allows the fraction of interaction-free measurements to be arbitrarily close to unity. Consider the arrangement in Fig. 1. A single photon is incident from the lower left port of a series of connected Mach-Zehnder interferometers. The reflectivity of each of the N beam splitters is chosen to be $R = \cos^2(\pi/2N)$, and the relative phases between corresponding paths in the upper and lower halves to be zero. In Fig. 1(a), the result is that the amplitude of the photon undergoes a gradual transference from the lower to the upper halves of the interferometers. This *coherent evolution* of the light from one stage to the next is essential here. After all N stages the photon will then with certainty exit via the "up" port of the final beam splitter.

In Fig. 1(b) we have inserted into the upper half of the system a series of detectors (all of which taken together constitute the "object" for this arrangement) which monitor the light at each stage. Now at each beam splitter there is only a small chance that the photon takes the upper path and triggers a detector, and a large probability $P = \cos^2(\pi/2N)$ that it continues to travel on the lower path instead. The *nonfiring* of each detector projects the state onto the lower half, and the whole process repeats [5]. Clearly, the probability that the photon is now found in the lower exit after all N stages is just the probability for it to have been reflected at each beam splitter:

$$P = \left[\cos^2\left(\frac{\pi}{2N}\right)\right]^N, \tag{2}$$

which in the limit of large N becomes $P = 1 - \pi^2/4N + O(N^{-2})$. Of course, the probability that one of the detectors *is* triggered is just the complement of (2), so that for a lossless system $\eta = P$ (Fig. 2). Already for $N \geq 4$ there is a greater than 50% probability of making an interaction-free measurement, thereby surpassing the limit of the original EV configurations. As the number of stages becomes very large, the efficiency of the scheme approaches 100%. From the perspective that each of the interrogations modifies the evolution of the wave function, thereby inhibiting the transference, our scheme may be considered an application of a discrete form of the quantum Zeno effect [4,6].

The expanded version of Fig. 1 was presented for pedagogical purposes. Using two identical "cavities" weakly coupled by a highly reflective beam splitter, one can realize a practical implementation in which the absorber is a *single* object (e.g., EV's ultrasensitive bomb; see Fig. 3). A photon is inserted into the left cavity at time $T = 0$. For timing purposes it is important that the length of the photon wave packet be shorter than the cavity length for the duration of the experiment. For a beam splitter reflectivity of $\cos^2(\pi/2N)$, and in the absence of any absorber, the photon will with certainty be located in the right cavity at time $T_N = N\times$(round-trip time), due to interference effects. Therefore, a detector inserted into the left cavity at time T_N would not fire. However, in the presence of an absorber or scatterer in the right cavity, the photon wave function is continually projected back onto the left cavity. Making the coupling weaker (i.e., increasing the reflectivity) and the number N greater, one can reduce

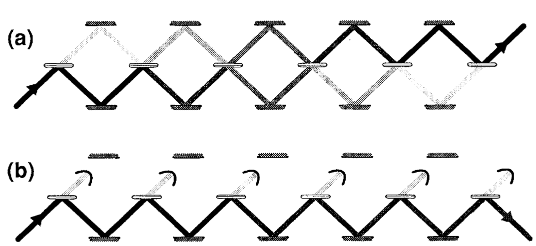

FIG. 1. The principle of coherently repeated interrogation: (a) A single photon incident from the lower left gradually transfers to the upper right half of the system. After N stages, where N depends on the beam splitter reflectivities, the photon will with certainty exit via the "up" port of the last beam splitter. (b) Introduction of detectors prevents the interference. At each stage the state is projected back into the bottom half of the system if the respective detector does *not* fire. After all the stages there is a large chance (2/3, for the example shown) that the photon now exits via the "down" port of the last beam splitter, indicating the presence of the detectors.

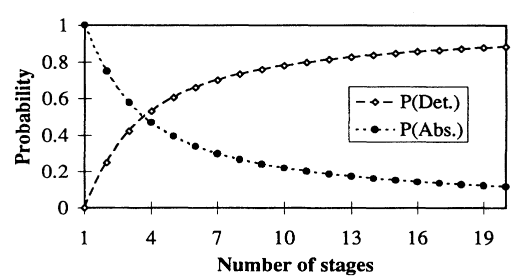

FIG. 2. The probability $P(\text{det})$ of an interaction-free measurement and the probability $P(\text{abs})$ that the photon is absorbed, i.e., that any of the internal detectors fire, for an incident photon in the setup in Fig. 1(b), as a function of the total number of stages, assuming ideal optical components.

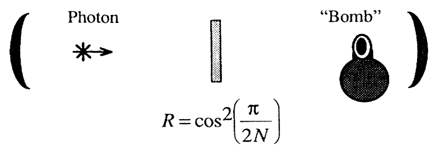

FIG. 3. One proposal for a high-efficiency interaction-free measurement system. In the absence of an object in the right cavity, a photon initially in the left cavity will with certainty be found in the right cavity after N cycles (where N depends on the precise value of the coupling beam splitter's reflectivity). With the object in, the photon will be found in the left cavity on the Nth cycle, with greater than 50% probability for $N \geq 4$. It is assumed that the cavity lengths are identical.

the probability that the photon ever leaves the first cavity when the object is in the second—now a detector inserted into the left cavity will nearly always fire at time T_N. Again, the probability of an interaction-free measurement can be made arbitrarily close to 100%.

It should be noted that the object need not be a classical device, but could be an atom, for instance, which is strongly coupled to the light field in the right-hand cavity of the system in Fig. 3. Assume that if the atom is in state A, a photon in the right cavity would with certainty be absorbed [7], leaving the atom in state B, the analog of triggering the "bomb." From B the atom decays rapidly (in a time less than the cavity round-trip time [5]) to a long lived state C. If the atom is not initially in state A, then over the course of N cycles a photon originally in the left cavity will "slosh" completely to the right cavity. Detecting the photon in the *left* cavity after N cycles gives definite information that the atom was in state A, without exciting it.

In considering interaction-free measurements on a quantum object, one must be careful to distinguish the present work from the ongoing efforts at quantum nondemolition (QND) measurements [8]. In the latter, one attempts to make a very precise measurement of some property of a quantum system (e.g., the number of photons in a beam) at the necessary expense of introducing noise into the conjugate variable (i.e., the phase of the light). Unlike QND, which is a *dispersive* technique, our *absorptive* method cannot distinguish between the presence of one object or more than one—both conditions effect the necessary "collapse."

A curious feature of the new proposal, also possibly relevant in practical implementations of high-efficiency interaction-free measurements, is that it enables the use of a classical pulse with an average photon number $\bar{n} > 1$ [9]. The probability of absorbing one of the photons equals $1 - \eta^n$, which can be made arbitrarily small for η sufficiently close to 1. Note, however, that this is not possible in the simpler EV scheme, where $\eta \leq 0.5$.

As an initial demonstration of the principle of interaction-free measurement, we performed an experiment using the correlated photon pairs produced via spontaneous parametric down-conversion. As is now well known, one can prepare an excellent approximation to a single-photon Fock state using the strong time and momentum correlations of these pairs [10]: Conditioned on the detection of one of the photons, the "trigger," one knows with certainty the existence of the conjugate photon. The use of such a single-photon state guarantees the mutual exclusivity of the possible outcomes in a given run [9]. In our experiment (Fig. 4) the down-conversion photon pairs were produced in a $LiIO_3$ crystal pumped by the 351 nm light from an argon-ion laser; photon pairs at 702 nm were selected using irises and 5 nm (FWHM) interference filters. We directed one member of each pair to the trigger detector D_T, the other one to a Michelson interferometer whose output port was monitored by detector D_{dark}. All detectors were avalanche photodiodes operated in the Geiger mode.

The interferometer operated within the "white-light fringe" region—the difference in path lengths was always less than 3 μm. The phase was piezoelectrically adjusted (and stabilized with an independent HeNe alignment laser and feedback system) to produce a minimum number of counts at D_{dark}; i.e., nearly all of the photons exited the interferometer via the entrance port. The remaining counts at D_{dark} constitute the background or noise of our detection scheme, arising from nonunity interference fringe visibility (in turn attributable to nonideal optical elements and imperfect alignment).

Using a translatable mirror, we could divert the light path from one of the interferometer arms to detector D_{obj}, thereby realizing the "object in" configuration (here we define the "object" to be the mirror + detector system). In a given run the coincidence rates C(dark) (between D_T and D_{dark}) and C(obj) (between D_T and D_{obj}) were recorded as the mirror was repeatedly inserted and removed [Fig. 5(a)]. The beam splitter in our interferometer was coated in five sections, each with a different reflectivity. Thus by horizontally translating the beam splitter in its plane, we were able to readily choose between reflectivities (measured directly with the down-conversion photons) of 54%, 43%, 33%, 19%, and 11%.

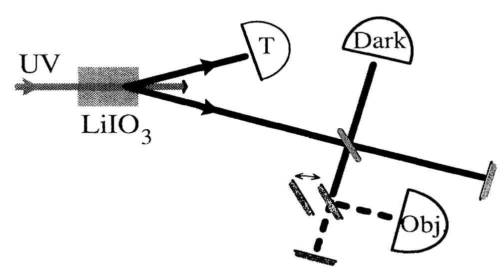

FIG. 4. Schematic of the down-conversion experiment demonstrating the principle of an interaction-free measurement.

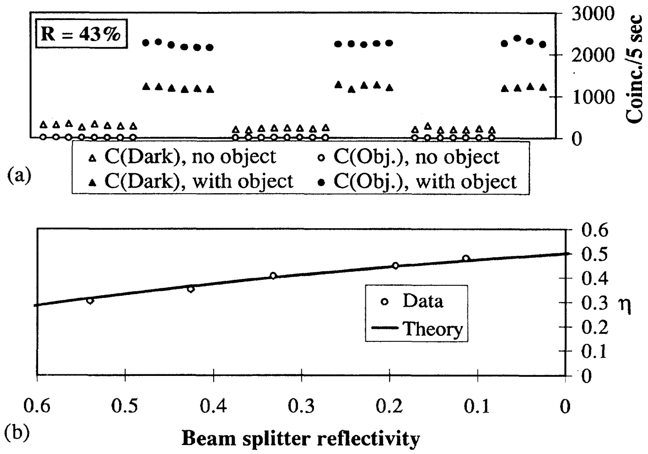

FIG. 5. (a) Typical experimental results for an interaction-free measurement. The beam splitter reflectivity for this data set was 43%. (b) Experimental and theoretical values for the figure of merit η in the Michelson-interferometer scheme, as a function of beam splitter reflectivity.

To obtain the figure of merit given in Eq. (1) from the experimental results, one must account for the finite detection efficiencies. For the purpose of our "proof of principle" experiment, it was convenient to equalize the net efficiencies of the detectors D_{dark} and D_{obj} [11]; under these conditions, we can replace $P(\mathrm{det})$ and $P(\mathrm{abs})$ of Eq. (1) with $C(\mathrm{dark})$ and $C(\mathrm{obj})$, respectively. The experimental results for the five reflectivities of our beam splitter are compared in Fig. 5(b) with the theoretical prediction.

We have presented here only the simplest schemes, assuming completely absorbing "objects," and lossless systems. The situation becomes much more complicated when these assumptions are relaxed, as we discuss elsewhere [12]. For example, the case of a semitransparent object can hardly be considered interaction free, as a photon passing *through* the object in general acquires a phase. The detrimental effects of losses depend on where they occur; e.g., equal losses at both end mirrors in the scheme in Fig. 3 do not affect the performance of the arrangement, other than to necessitate repetition. Finally, losses in the form of low detector efficiencies can be much less problematic with the new proposal than for the EV scheme, precisely because η can be close to 1.

In summary, we have demonstrated in our Michelson-interferometer experiment an interaction-free measurement for which η is nearly $1/2$. However, if one uses coherently repeated weak interrogations, this fraction can be made arbitrarily close to 1. It is clear that there are many methods for achieving these high-efficiency tests: Because of the isomorphism of all two-state systems, it is possible to use these techniques with any two-level scheme. For example, in [4] we consider a polarization-based system where the object inhibits the stepwise rotation of the polarization of a photon. We have performed a preliminary experiment of this type, and were able to detect a *polarization*-sensitive object (i.e., a polarizing beam splitter) with an η of $2/3$. Experiments are currently in progress to demonstrate the high-efficiency interaction-free measurement of *any* non-transmitting object, based on the schemes discussed here.

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