ISBN 2-86332-169-2

Editions Frontières
B. P. 33
91192 Gif-sur-Yvette Cedex - France

Printed in Singapore

EXPERIMENTAL REALIZATION OF "INTERACTION-FREE" MEASUREMENTS

Paul Kwiat, Harald Weinfurter, Thomas Herzog, Anton Zeilinger
Institut für Experimentalphysik
Universität Innsbruck, 6020 Innsbruck
AUSTRIA

Mark Kasevich
Department of Physics
Stanford University, Palo Alto, CA 94305
USA

We have demonstrated experimentally that one can ascertain the presence of an object inside an interferometer without interacting with it. The simplest scheme uses photons incident on a Michelson interferometer. With a 50-50 beam splitter, 33% of the measurements can be interaction-free. We also propose a novel scheme in which the fraction of interaction-free measurements can be arbitrarily close to 1. In the new scheme we interrogate the region with the object many times, but only weakly.

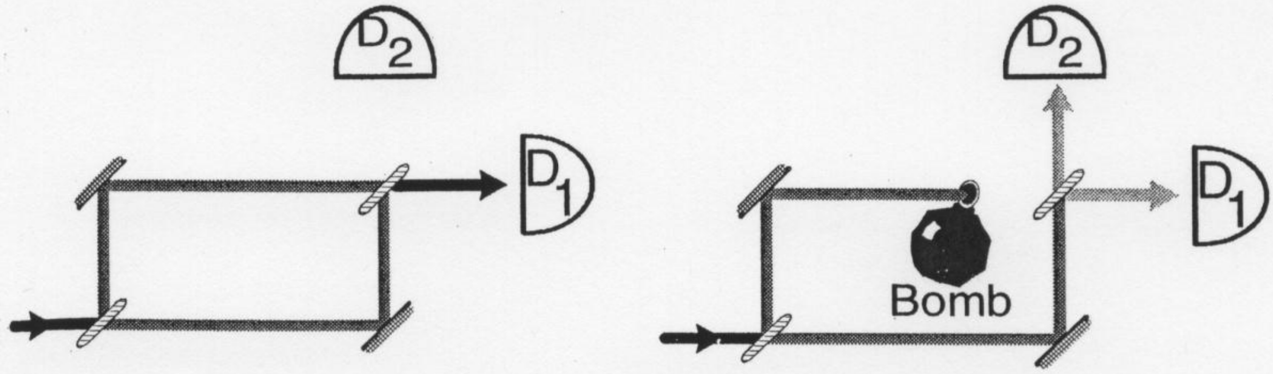
I. Introduction

Recently, Elitzur and Vaidman have pointed out that it is possible to make "interaction-free" quantum mechanical measurements, in which the existence of an object in a given region of space may be ascertained seemingly without interacting with it[1),2)]. This possibility is nonclassical, in that it relies on the wave-particle duality. The initial proposal employed a Mach-Zehnder interferometer (see Fig. 1a), aligned so that incident photons (or any other interfering particles) exit to detector D_1 with certainty, in the absence of any object within the interferometer. Thus detector D_2 *never* fires under this configuration. The presence of an absorbing (or more generally, non-transmitting) object in one of the arms changes completely the possible outcomes. For a 50-50 beam splitter, the photon will encounter the object with 50% probability and be absorbed. To make the argument more dramatic, Elitzur and Vaidman included the notion that this absorption of a single photon would trigger the explosion of an ultra-sensitive bomb. There is a 25% probability that the photon will still exit port #1, yielding no information. However, there is also a 25% probability that the photon will exit via the *other* exit port, to detector D_2. Detecting this photon one can conclude that an object was certainly within the interferometer, even though the photon could not have interacted with it, in the standard sense! Put differently, one has managed to detect the presence of the ultra-sensitive bomb without triggering it, an impossible feat in classical physics.

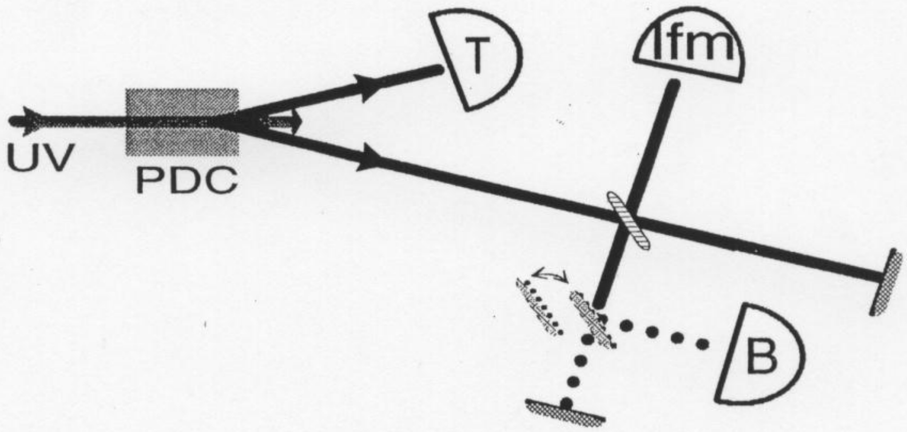
If one performs the above procedure only once, it is clear that one can have interaction-free verification of the presence of the bomb only 25% of the time. However, by repeating the experiment or recycling the photon in cases where it leaves the interferometer by port #1, one can increase the total probability of an interaction-free measurement. A useful figure of merit in evaluating any potential scheme is the following:

$$\eta = \frac{P(Det\,2)}{P(Det\,2) + P(boom)} \qquad (1)$$

For a lossless system, this is basically the probability of making an interaction-free



a.



b.

Fig. 1a. Simple Mach-Zehnder interferometer, with and without a sensitive bomb-trigger in one path. b. Schematic of down-conversion experiment to demonstrate the principle of interaction-free measurement.

measurement, or the fraction of bombs that can be saved. The fraction of measurements that can be interaction-free is thus 1/3 for the simple case considered above.

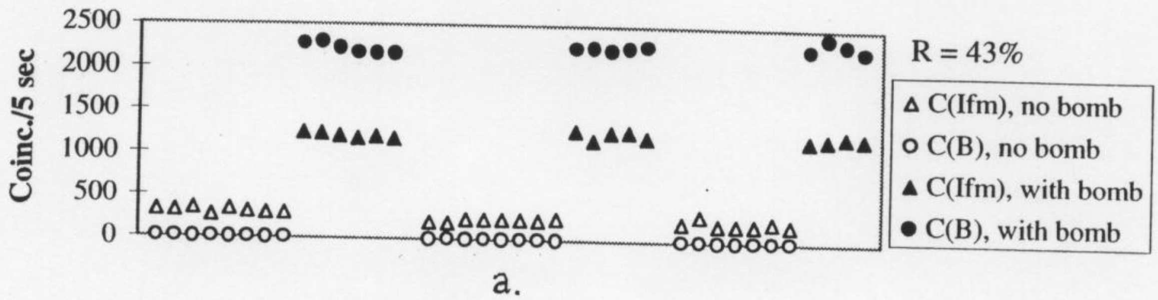
It is important to stress why this is a quantum-mechanical effect. It is certainly true that using purely classical field calculations, one arrives at the same probabilities appearing in (1). The difference is that with a classical field it is possible for both detector 2 *and* the bomb detector to be triggered in a given run. However, if we use a single-photon state, this outcome is impossible. Complementarity is essential: In the absence of the object, it is the wave-like nature of the incident quantum which allows us to establish, through destructive interference, a condition in which detector 2 never fires; in the presence of the object, it is the indivisibility of the quantum which enforces the mutual exclusivity of the possible outcomes.

II. Experimental Description

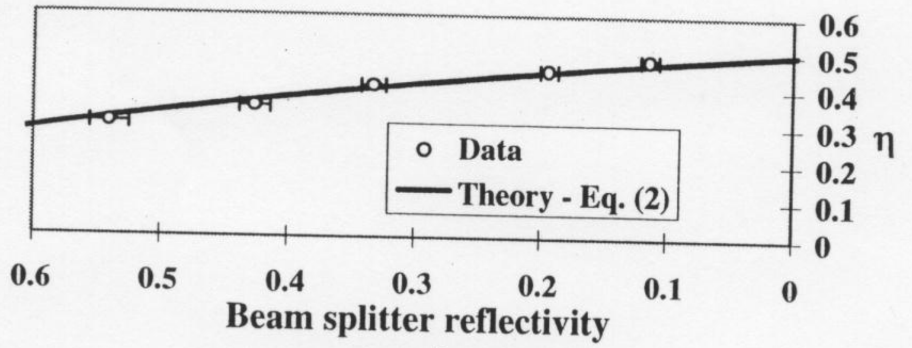
In our experiment (Fig. 1b) pairs of correlated photons were produced via the process of spontaneous parametric down-conversion in a nonlinear crystal ($LiIO_3$). The pump beam at 351 nm originated in an argon-ion laser; using irises and 5-nm (FWHM) interference filters, we selected down-converted photon pairs at 702 nm. One member of each pair was directed to the "trigger" detector D_T, the other one to a Michelson interferometer, adjusted to lie within the "white-light fringe" region so that the difference in path lengths was always less than 3 μm. The detector D_{Ifm} looked at the output port of the interferometer. By means of a removable mirror, it was possible to direct the photons from one of the arms to the detector D_B, thereby producing the "bomb in" configuration. In the absence of the "bomb mirror" the path difference in the interferometer was adjusted to produce a minimum number of counts at D_{Ifm}, i.e., most of the photons exited the interferometer via the entrance port.

It has been previously shown that by counting the down-conversion photons in coincidence, one may prepare a very good approximation to a single-photon Fock state[3)]. Therefore, our data consist of various coincidence rates between D_T and D_{Ifm}, and between D_T and D_B. After locking our interferometer to a minimum of D_{Ifm}, data were recorded, periodically switching from a "bomb out" to a "bomb in" configuration. Typical results are shown in Fig. 2a, where the open and filled symbols refer to the "bomb out" and "bomb in" conditions, respectively. Even in the absence of a bomb, the data still display counts at D_{Ifm}, falsely indicating the presence of the bomb mirror. These counts constitute the "dark counts" or noise of our detection scheme, arising from accidental coincidences and non-unity interference fringe visibility.

The beam splitter in our interferometer was a 1-mm thick glass plate, with one side anti-reflection coated, and the other side 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%, without changing the relative path lengths in the interferometer. The expected figure of merit (1) when the



a.



b.

Fig. 2a. Typical experimental results for an interaction-free measurement (see Fig. 1b). The open (filled) symbols refer to the "bomb out" ("bomb in") condition. b. Experimental and theoretical values for the figure of merit η in a Michelson-interferometer scheme, as a function of beam splitter reflectivity.

omb mirror is inserted can easily be generalized to a function of beam splitter eflectivity. In the absence of losses, the probability of an incident photon going owards the bomb is R, while the probability of it going towards the interferometer etector is RT. Assuming a lossless beam splitter, T = 1 - R, we have

$$\eta = \frac{RT}{RT+R} = \frac{1-R}{2-R}, \tag{2}$$

plot of which is given in Fig. 2b. To obtain the figure of merit described by Eq. (2) rom the experimental results, one must account for the finite detector efficiencies. or the purpose of this "proof of principle" experiment it was convenient to equalize to within 0.06%) the net detection efficiencies of the bomb detector D_B and the inter-erometer detector D_{Ifm} by adjusting the detector overbiases (the actual efficiencies vere approximately 2%). Under these conditions the efficiencies cancel out of (2) nd one may simply use the rates directly: $\eta = C(Ifm)/[C(Ifm)+C(B)]$. The xperimental results for the five regions on our beam splitter are displayed in Fig. 2b.

III. High-Efficiency Interaction-Free Measurements

Note from Eq. (2) that as the reflectivity becomes small, the fraction of interaction-free measurements tends to the value 50%. As previously stated by Elitzur and Vaidman[2], this is the upper limit possible with the interferometer schemes discussed thus far. We have recently discovered that one may exceed this limit by using an application of the Quantum Zeno effect[4),5)]. Indeed, in principle the fraction of interaction-free measurements may be made arbitrarily close to unity! Recall that in the Zeno effect the evolution of a quantum system is altered by repeated measurements made on the system. We have performed a simple experiment to illustrate the optical version of the Quantum Zeno effect presented in Fig. 3. In our experiment (described elsewhere[6)]) rather than employing 6 different polarization rotators and 6 different polarizers, we sent our photons in a spiral through the same

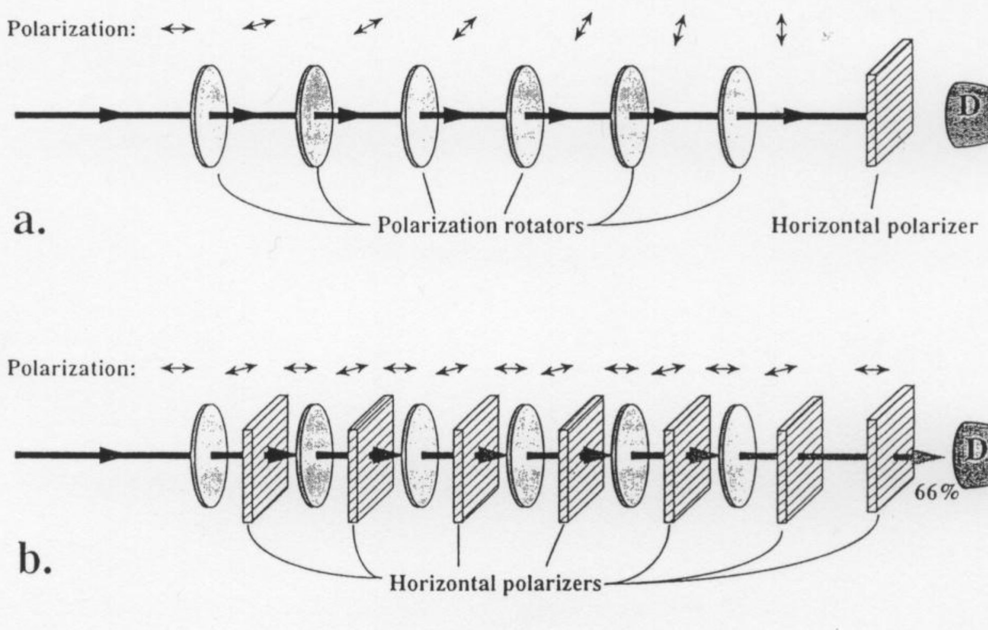


Fig. 3 Simple optical version of the Quantum Zeno effect[6)]. a.) A series of polarization rotators are used to rotate the polarization of the input photon from horizontal to vertical. No light is seen at the final detector. b.) When a series of horizontal polarizers are interspersed between the rotators, the light is at every stage projected back onto a state of horizontal polarization, resulting in light at the final detector. If the number of stages is ≥ 4, more than 50% of the input light will be transmitted. In particular, for the case shown ($N = 6$), the chance of transmission is very nearly twice the chance of absorption.

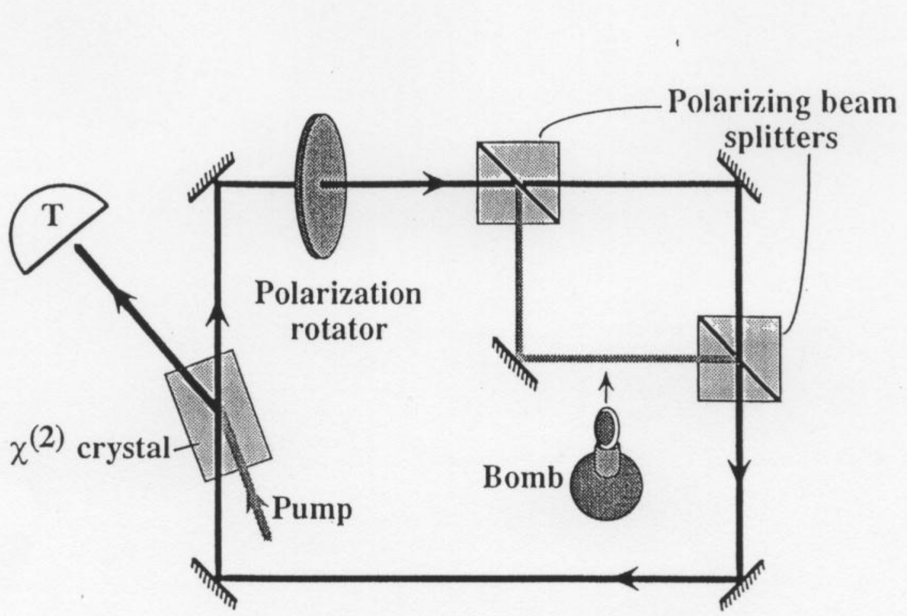


Fig. 4 Simplified scheme to observe greater than 50% interaction-free measurement. The down-conversion photon makes N cycles before being removed (due to geometry or a fast switch) and its polarization measured.

components 6 times. The experiment may be interpreted as a limited version of a true high-efficiency interaction-free measurement scheme: One is able to detect a *polarization-sensitive* bomb more than 50% of the time without losing the incident photon. Consider now the related scheme in Fig. 4. Single-photon states are produced using correlated down-conversion photons. One of the photons is used again as a trigger, while the other photon makes a specified number of cycles in the system before being detected. The number of cycles is determined either from geometry (e.g., the photon spirals up in the loop, until it passes over one of the components) or with fast timing (based on the arrival time of the trigger photon, a fast switch [not shown] can be used to direct the other photon out of the system after N cycles). We choose the value of the polarization rotation to be $\pi/2N$, so that in the absence of any bomb, the initially horizontally-polarized photon is found after N cycles to be vertically-polarized*.

---

*To meet this condition it is important that the path lengths in the internal Mach-Zehnder interferometer (upper right corner, with polarizing beam splitters) be the same to within 2π; otherwise, incident linear polarization can become elliptical, due to the relative phase shift between the vertical and horizontal components.

The presence of a "bomb" or any non-transmitting object in the lower path of the internal Mach-Zehnder changes the situation completely. Now with each cycle there is only a small chance that the photon chooses this lower path and triggers the bomb, and a large probability $P = \cos^2(\pi/2N)$ that it travels the upper path instead. In this second possibility, the polarization after the recombining polarizing beam splitter is once again horizontal, and the whole process repeats. Clearly, the probability that the photon is found after N cycles to be still horizontally-polarized is just the probability for it to have taken the upper path during each cycle:

$$P = \left[\cos^2\left(\frac{\pi}{2N}\right)\right]^N, \tag{3a}$$

which in the limit of large N becomes

$$P = 1 - \frac{\pi^2}{4N} + O\left(\frac{1}{N^2}\right). \tag{3b}$$

Of course, the probability that the bomb is triggered is just the complement of (3). Eq. (3a) is plotted in Fig. 5. One sees immediately that as long as $N \geq 4$, there exists a greater than 50% probability of making an interaction-free measurement, thereby surpassing the "limit" of the original Elitzur-Vaidman configurations discussed in Sects. I-II.

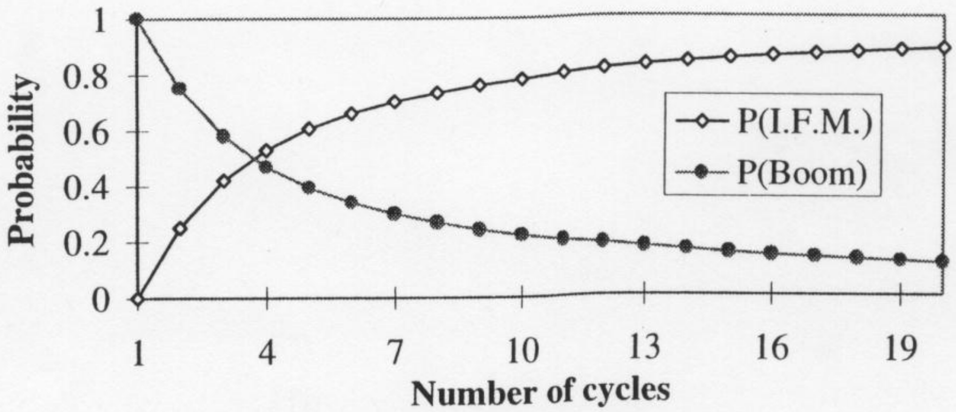


Fig. 5 The probability P(I.F.M.) of interaction-free measurement and the probability P(Boom) that the bomb is triggered, for incident photons in the setup in Fig. 4, as a function of the total number of cycles, assuming ideal optical components.

It should be noted that the use of polarization is not essential for these high-efficiency tests. Due to the isomorphism of all two-state systems, it should be possible to use these techniques with any two-level scheme. For example, using two identical cavities that are weakly coupled by a highly reflective beam splitter, one can realize a practical implementation (see Fig. 6). A photon is inserted into the left cavity at time $T = 0$. If the beam splitter reflectivity is given by $\cos^2(\pi/2N)$, then in the absence of any absorber the photon will with certainty be located in the right cavity at time $T_N = N$ x (round-trip time), so long as the lengths of the two coupled cavities are identical. This is true even if the coherence length of the photon wave packet is much shorter than the cavity length. Therefore, a detector inserted into the left cavity at time T_N would not fire. However, in the presence of an absorber or scatterer (e.g., our ultra-sensitive bomb) in the right cavity, the photon wavefunction is continually projected back onto the left cavity. By making the coupling weaker (and the number N greater), one can arbitrarily reduce the probability that the photon ever leaves the first cavity when the bomb is in the second--now a detector inserted into the left cavity will nearly always fire at time T_N. Consequently, one can in principle make the probability of an interaction-free measurement arbitrarily close to 1.

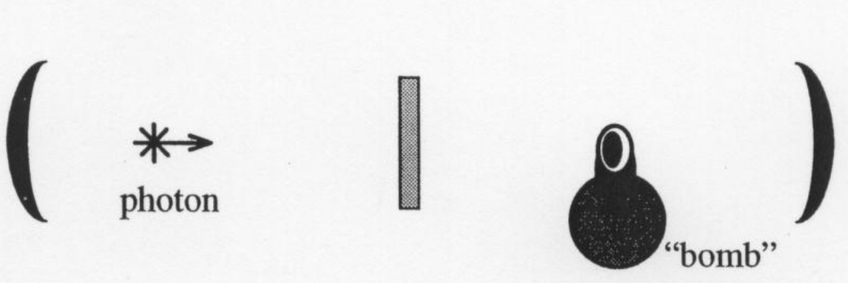


Fig.6 A purely interferometric interaction-free measurement system. In the absence of a bomb in the right cavity, a photon initially in the left cavity will with certainty be found in the right cavity after N cycles (where N depends on the precise value of the coupling beam splitter's reflectivity R). With the bomb, and when $N \geq 4$, the photon will more likely be found in the left cavity on the Nth cycle. It is assumed that the cavity lengths are identical.

Again, down-converted photons are an appropriate choice, because the strong time correlations yield exact information as to when one should "insert" a detector into the cavity. Also, one has the capability of actually creating one of the down-converted photons *inside* the cavity, removing the need for some kind of optical switch at this stage. In practice, losses reduce the effectiveness of such schemes, but it should still be possible in a real setup to have interaction-free measurements more than half of the time.

In summary, we have demonstrated in our Michelson-interferometer experiment an interaction-free measurement with a figure of merit η up to 1/2, i.e., half of our measurements could be interaction-free. In the Zeno experiment discussed elsewhere[7)], we were able to detect a polarization-sensitive bomb with an η of 2/3. Work is currently in progress to demonstrate the high-efficiency interaction-free measurement of *any* non-transmitting bomb, based on the repeated-interrogation schemes presented here.

Acknowledgments: This work was supported by the Austria Science Foundation (FWF), Project No. S065/02. One of us (P. G. K.) was supported by FWF Lise Meitner Postdoctoral Fellowship, M0077-PHY.

REFERENCES

[1)] ELITZUR, A. & L. VAIDMAN. 1993. Found. Phys. **23**: 987.
[2)] VAIDMAN, L. *To appear in* Quantum Optics.
[3)] HONG, C. K. & L. MANDEL. 1986. Phys. Rev. Lett. **56**: 58.
[4)] MISRA, B. & E. C. G. SUDARSHAN. 1977. J. Math. Phys. **18**: 756.
[5)] PERES, A. 1980. Am. J. Phys. **48**: 931.
[6)] KWIAT, P. G., H. WEINFURTER, T. HERZOG & A. ZEILINGER. *In* Proceedings of the Conference on Fundamental Problems in Quantum Theory, held in honor of Prof. J. A. Wheeler, UMBC, Baltimore, Maryland June 19-22, 1994. Annals of the New York Academy of Science.