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Interaction-Free Measurements

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1 The Penrose bomb testing problem

I am greatly indebted to Roger Penrose. I have learned very much from his papers, from his exciting books, and from our (too short) conversations. I am most grateful to Roger for developing the idea of Avshalom Elitzur and myself on interaction-free measurements (IFM). The version of IFM Penrose described in his book (1994) is conceptually different from our original proposal, and although it is much more difficult for practical applications it has the advantage of demonstrating even more striking quantum phenomena. So I will start with presenting Penrose's version of IFM.

Suppose we have a pile of bombs equipped with super-sensitive triggers. The good bombs have a tiny mirror which is connected to a detonator such that if any particle (photon) "touches" the mirror, the mirror bounces and the bomb explodes. Some of the bombs are duds in which the mirror is rigidly connected to the massive body of the bomb. Classically, the only way to verify that a bomb is good is to touch the mirror, but then a good bomb will explode. Our task is to test a bomb without exploding it. We are not allowed to make errors in our test, i.e., to say that a bomb is good while it is a dud, but we may sometimes cause an explosion.

There cannot be a solution by weighing the bomb, or touching the mirror from the side, or any other similar way: the only observable physical difference between a good bomb and a dud is that the good bomb will explode when a single particle will touch the mirror, and the dud will not. Thus, the solution of this task seems to be logically impossible: the only difference between the bombs is that one explodes and the other does not and we are asked to test a bomb without exploding it. Nevertheless, quantum mechanics provides a solution to the problem in a surprisingly simple way.

The method uses the well known Mach-Zehnder interferometer which is shown in Fig. 1. The photons reach the first beam splitter which has transmission coefficient 1/2. The transmitted and reflected parts of their waves are then reflected by two mirrors and finally reunite at another similar beam splitter. Two detectors collect the photons after they pass through the second beam splitter. It is

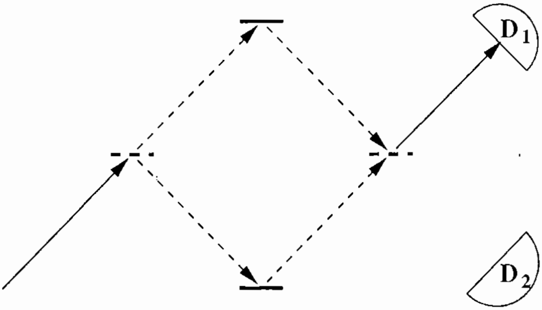

FIG. 1. **Mach-Zehnder Interferometer.** When the interferometer is properly tuned, all photons are detected by D_1 and none reach D_2. The mirrors must be massive enough and have well-defined position.

possible to arrange the positions of the beam splitters and the mirrors in such a way that due to destructive interference no photons are detected by one of the detectors, say D_2, and they all are detected by D_1.

In order to test a bomb we have to tune the interferometer in the way indicated above and replace one of its mirrors by the mirror-trigger of the bomb, see Fig. 2. We send photons through the system. If the bomb is a dud then only detector D_1 clicks. If, however the bomb is good then no interference takes

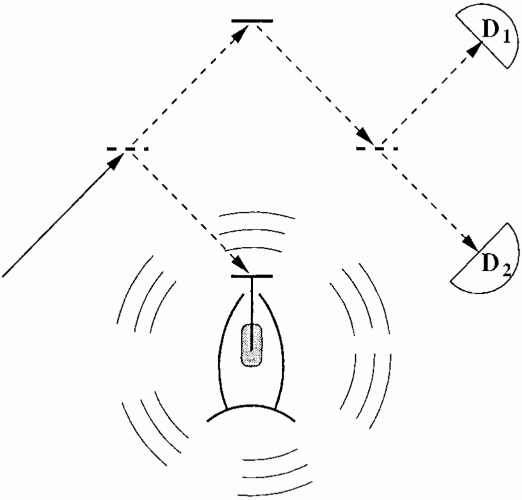

FIG. 2. **The Penrose bomb-testing device.** The mirror of the good bomb cannot reflect the photon, since the incoming photon causes an explosion. Therefore, D_2 sometimes clicks. (The mirror of a dud is connected to the massive body, and therefore the interferometer "works", i.e. D_2 never clicks.)

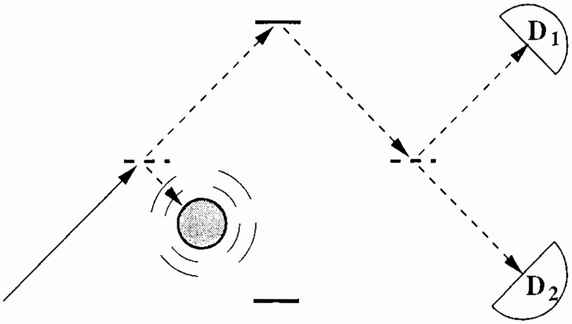

FIG. 3. **Finding an ultra-sensitive mine without exploding it.** If the mine is present, detector D_2 has probability 25% to detect the photon we send through the interferometer and in this case we know that the mine is inside the interferometer without exploding it.

place and there are three possible outcomes: the bomb might explode (probability 1/2), detector D_1 might click (probability 1/4), and detector D_2 might click (probability 1/4). In the latter case we have achieved our goal: we know that the bomb is good (otherwise D_2 could not click) without exploding it.

2 The Elitzur–Vaidman bomb testing problem

Although conceptually Penrose's proposal for testing bombs is very interesting, its implementation is very difficult. The tricky part is replacing the mirror of a tuned interferometer by the bomb. Usually, replacing a mirror requires re-tuning the interferometer, but here it is impossible to do that (the bomb might explode while we are re-tuning). The original bomb testing problem (Elitzur and Vaidman, 1993) is slightly less dramatic, but it can and has been implemented in a real experiment. This problem is equivalent to the task of finding an ultra-sensitive mine without exploding it. The solution is similar to the above: we tune the Mach-Zehnder interferometer to have no photons detected by D_2. Then we place the interferometer in such a way that the mine (if present) blocks one of the arms of the interferometer, see Fig. 3. All the discussion above about the operation of the device is the same, but the main difficulty is absent: there is no need to fix the exact position of the mine.

The efficiency of finding a good bomb (mine) without exploding it in the above procedure is only 25%. By modifying the transmission coefficients of the beam splitters and repeating the procedure in case of no explosion we can (almost) reach the efficiency of 50%. Even more surprisingly, the efficiency can be made as close as we want to 100% by integrating the idea of the IFM with the quantum Zeno effect, see Kwiat *et al.* (1995).

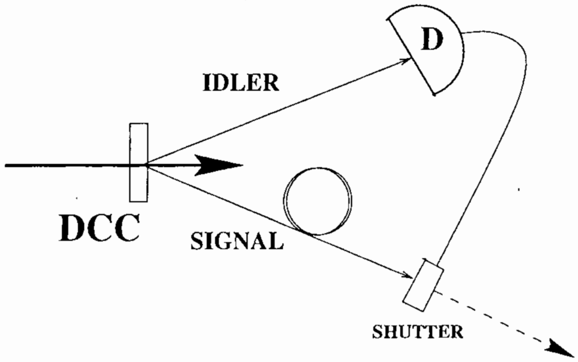

FIG. 4. **Single-photon gun.** The signal photon comes from the down-conversion crystal DCC and stored in the delay ring during the time that the idler photon activates a detector which sends a fast electronic signal to open a shutter for a short time on the way of the signal photon.

3 Experimental realization of the IFM

Two experiments verifying IFM have been performed. The first (Kwiat *et al.* 1995) used a down-conversion crystal as a photon source and state of the art optical components. The "bomb" was an efficient detector and the "explosion" was a registration of the count by a computer. A statistical analysis of thousands of counts was performed and, after normalization according to the noise and the efficiency of the detectors, the results confirmed the prediction of quantum theory with a very good precision. The second experiment was performed as a demonstration at the science fair in Groningen (du Marchie van Voorthuysen, 1997). In this experiment a standard Mach-Zehnder interferometer was operated. Occasionally a detector (connected to a loud bell in order to simulate the explosion) was inserted along one arm of the interferometer. A dimmed laser light entered the interferometer. The visitors could see that without the bell-detector usually D_1 clicked first. When the bell-detector was present, in most of the cases they first heard the bell, sometimes D_1, but also, in many cases D_2 clicked first, thus telling us that the bell-detector is inside the interferometer.

The technical achievements of the two experiments cannot be compared, but the latter had one advantage: it was really testing (although inefficiently and not very reliably) the presence of the bomb (the bell-detector). The first experiment was much more precise, but it was used more to test quantum mechanics, than to find an object without "touching" it. In the experimental run the detector which played the role of the bomb was triggered many many times. It can be considered an IFM only during the short time windows defined by the clicks of the detections of the "idler" photons coming from the down-conversion crystal.

This type of experiment with coincidence counts is commonly considered as "a single-photon" experiment. (In the Groningen experiment there was no attempt to use a single-photon source at all.) I think, however, that it is conceptually important to perform an IFM with a real single-photon source, a device which emits when commanded just one photon. I may call it a single-photon gun, see Fig. 4. In such an experiment there is another paradoxical aspect: we can get information about a region of space never visited by any particle, see Vaidman (1994a).

4 Generalized IFM

Let us consider now a more general task which can be considered as an IFM, see Vaidman (1994b). We have to verify that the system is in a certain state, say $|\Psi\rangle$. The state $|\Psi\rangle$ is such that its detection causes an explosion or destruction: destruction of a system, of a measuring device, or at least of the state $|\Psi\rangle$ itself. The states orthogonal to $|\Psi\rangle$ do not cause the destruction. Although the only physical effect of $|\Psi\rangle$ is an explosion which destroys the state, we have to detect it without any distortion.

Let us assume that if the system is in a state $|\Psi\rangle$ and a part of the measuring device is in a state $|\Phi_1\rangle$, we have an explosion. For simplicity, we will assume that if the state of the system is orthogonal to $|\Psi\rangle$ or the part of the measuring device which interacts with the system is in a state $|\Phi_2\rangle$ (which is orthogonal to $|\Phi_1\rangle$) then neither the system nor the measuring device changes their state:

$$\begin{aligned} |\Psi\rangle\ |\Phi_1\rangle &\rightarrow |expl\rangle \\ |\Psi_\perp\rangle|\Phi_1\rangle &\rightarrow |\Psi_\perp\rangle|\Phi_1\rangle \\ |\Psi\rangle\ |\Phi_2\rangle &\rightarrow |\Psi\rangle\ |\Phi_2\rangle \\ |\Psi_\perp\rangle|\Phi_2\rangle &\rightarrow |\Psi_\perp\rangle|\Phi_2\rangle. \end{aligned} \tag{4.1}$$

Now, let us start with an initial state of the measuring device $|\chi\rangle = \alpha|\Phi_1\rangle + \beta|\Phi_2\rangle$. If the initial state of the system is $|\Psi\rangle$, then the measurement interaction is:

$$|\Psi\rangle|\chi\rangle \rightarrow \alpha|expl\rangle + \beta|\Psi\rangle|\Phi_2\rangle = \alpha|expl\rangle + \beta|\Psi\rangle(\beta^*|\chi\rangle + \alpha|\chi_\perp\rangle), \tag{4.2}$$

where $|\chi_\perp\rangle = -\beta^*|\Phi_1\rangle + \alpha|\Phi_2\rangle$. If, instead, the initial state of the system is orthogonal to $|\Psi\rangle$, then the measurement interaction is:

$$|\Psi_\perp\rangle|\chi\rangle \rightarrow |\Psi_\perp\rangle|\chi\rangle. \tag{4.3}$$

To complete our measuring procedure we perform a measurement on the part of the measuring device to distinguish between $|\chi\rangle$ and $|\chi_\perp\rangle$. Since there is no component with $|\chi_\perp\rangle$ in the final state (4.3), it can be obtained only if the initial state of the system had the component $|\Psi\rangle$. This is also the final state of the system: we do not obtain $|\chi_\perp\rangle$ in the case of the explosion.

A Mach-Zehnder interferometer is a particular implementation of this scheme. Indeed, the photon entering the interferometer can be considered as a measuring device prepared by the first beam splitter in a state $|\chi\rangle = \frac{1}{\sqrt{2}}(|\Phi_1\rangle + |\Phi_2\rangle)$, where $|\Phi_1\rangle$ designates a photon moving in the lower arm of the interferometer, and $|\Phi_2\rangle$ designates a photon moving in the upper arm. Detector D_2 together with the second beam splitter tests for the state $|\chi_\perp\rangle = \frac{1}{\sqrt{2}}(|\Phi_1\rangle - |\Phi_2\rangle)$.

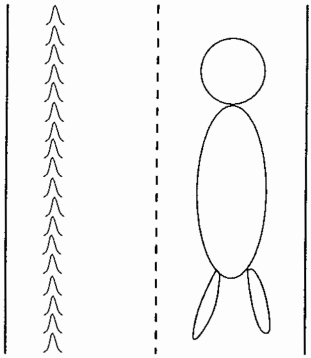

FIG. 5. **Safe X-ray photography.** Between two parallel mirrors another mirror which reflects 99.9% and transmits 0.1% is introduced. A photon starting on the left side will then end up on the right side after about 50 bounces. If, however, on the right side there is an object which can absorb the photon, then with 95% probability the photon will stay on the left. To make a photographic picture, a person enters into the right side and the photons are placed on the left side. After the time required for 50 bounces a photographic plate is introduced in the left side. In such an experiment the bones absorb only 5% of the radiation, i.e. twenty times less than in the the standard method. (It is assumed that the soft tissue does not affect the X-rays at all, while the bones are opaque.)

5 Applications of the IFM

In principle, the IFM may have many dramatic practical applications. For example, if we have a method of selecting a certain bacteria which also kills it, the IFM may allow us to select many such live bacteria. One can fantasize about safe X-ray photography, see Fig. 5. One can design a scheme of a computer which will allow knowing the result of a computation without computing, see Jozsa (1996). These are gedanken ideas, but I am optimistic about finding situations in which the IFM will have some real practical applications.

6 The IFM as counterfactuals

The IFM also has interesting philosophical implications. Let me quote Roger Penrose (1994, p.240):

> What is particularly curious about quantum theory is that there can be actual physical effects arising from what philosophers refer to as *counterfactuals* – that is, things that might have happened, although they did not happen.

For me this paradoxical situation gives another reason why we should accept the many-worlds interpretation (MWI) of quantum theory. According to the MWI, in the situations considered by Penrose, "things" did not happen in a particular world, but did happen in some other world (see Vaidman 1994a). Therefore, they did take place in the physical universe which incorporates all the worlds and thus their effect is not so surprising.

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