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LETTER TO THE EDITOR

On the realization of interaction-free measurements

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Abstract. A possible realistic implementation of a method for interaction-free measurements, due to Elitzur and Vaidman, is proposed and discussed. It is argued that the effect can be observed in an optical laboratory.

The interaction-free measurements of Elitzur and Vaidman [1] is a proposal to consider a well known device and ask a question which is, in a sense, opposite to what is usually asked. The suggested procedure achieved a surprising result which is a complete contradiction to classical intuition.

Assume that an experimentalist claims he has built a super-detector with an efficiency of 100% for all kinds of particles (including photons). He says that it is now on a table in a dark room and it is ready to count particles coming from all directions. You, however, suspect that there is nothing on the table. Is it possible to find out which one of these possibilities is true without the detector (if it is really there) counting any particle? Classically, the only way to verify the existence of the detector requires sending it some test particles. However, then the detector invariably clicks. The task of locating the detector without the occurrence of any click seems to be impossible. Remarkably, quantum mechanics allows this, with, however, one reservation: we do not always succeed in finding it without the click.

Our method is based on the Mach–Zehnder interferometer used in classical optics. In principle, it can work with any type of particle. The particle reaches the first beamsplitter which has transmission coefficient $\frac{1}{2}$. The transmitted and reflected parts of the particle's wave are then reflected by the mirrors and finally reunite at another similar beamsplitter (figure 1(*a*)). Two detectors collect the particles after they pass through the second beamsplitter. We can arrange the positions of the beamsplitters and the mirrors such that because of destructive interference, no particles are detected by one of the detectors, say D_2, and all are detected by D_1. We position the interferometer in such a way that one of the routes of the particle passes through the place where the super-detector might be (figure 1(*b*)). We send a single particle through the system. There are three possible outcomes of this measurement: (i) the super-detector clicks, (ii) detector D_1 clicks, (iii) detector D_2 clicks.

The probability for the first case is $\frac{1}{2}$. In the second case (for which the probability is $\frac{1}{4}$), the measurement does not succeed either. The particle could have reached D_1 in both cases: when the super-detector is, and when it is not there. Finally, in the third case, when the detector D_2 clicks (the probability for which is $\frac{1}{4}$), we have achieved our goal: we know that the super-detector is inside the interferometer and it did not click.

Let us estimate now the probability for a successful experiment. Even the ideal experiment does not always succeed. We have seen that the probability for success here is

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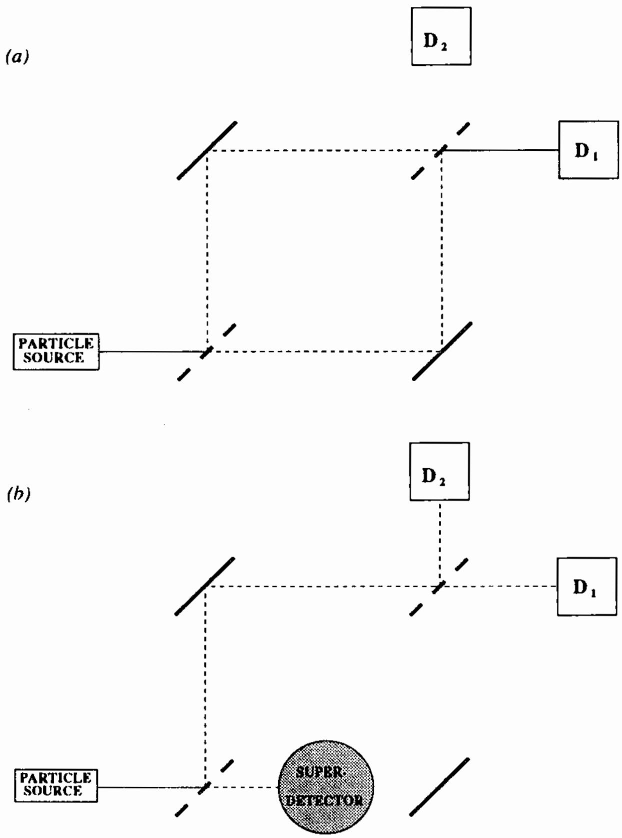

Figure 1. (*a*) If there is no object inside the interferometer, D_2 never clicks. (*b*) When D_2 clicks after sending just one particle we know that the super-detector is inside the interferometer although it did not count any particle.

only $\frac{1}{4}$. But we also have the probability $\frac{1}{4}$ not to trigger the super-detector without finding it. Trying again and again, until success or the click, leads to the probability $\frac{1}{3}$ of locating the untriggered super-detector. We have shown [1] that by modifying the transmission coefficients of the beam splitters in the interferometer we can obtain (almost) a probability $\frac{1}{2}$ for success.

This is, however, a gedanken experiment. A super-detector with 100% efficiency, a Mach–Zehnder interferometer with complete destructive interference in one detector, a single particle source—these are not devices that can be found in a standard laboratory. Let us now discuss a few points which are relevant for a realization of the idea in a real laboratory.

We do not need a super-detector sensitive to all kinds of particles. It can be replaced by a photon detector of a certain energy range, while we restrict ourselves to use only such photons.

We do not need a source of single photons. We assume that the click is loud enough for us to hear, so all we need is a *weak* source of photons and *fast* switch that stops the beam when detector D_2 clicks. (The single-photon source [2] is necessary if we want to locate an object and be sure that it was not disturbed in any way whatsoever, even if the object does not click.)

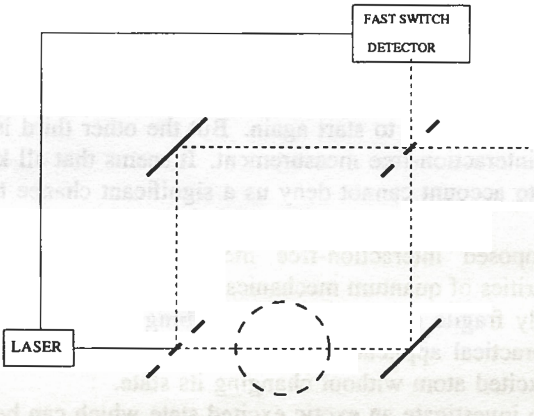

Figure 2. A fast switch detector stops the beam when it detects a photon. We can learn about the existence of an object inside the interferometer by measuring the time it takes for the detector to click starting from the beginning of the run.

We do not need 100% efficiency in detector D_2. Of course, low efficiency will reduce the probability of detecting the object, but if the detector clicks, we are still 100% sure that the object is there.

If we have an ideal interferometer, we do not need a super-detector with 100% efficiency such that every photon is *invariably* detected. It is enough for the photon to have just finite probability to be absorbed (to be scattered, to change its phase). Even the probability for the success remains unchanged, we only need to put more photons through the interferometer.

If we have an ideal equal-path interferometer, we do not need a monochromatic source: complete destructive interference occurs for all wavelengths.

Unfortunately, we do not have an ideal Mach–Zehnder interferometer. There is no possibility of obtaining 100% destructive interference in the detector D_2. Sometimes we will get clicks even if there is nothing inside the interferometer. Also, we will get wrong clicks due to noise in the detector D_2.

Let us now discuss a proposal for demonstration of the interaction-free measurement in a laboratory. In a modern laboratory one can obtain the ratio of 1:100 for the number of clicks in the detectors D_2 and D_1 when there is no object inside the interferometer (instead of the theoretical 0 counts for detector D_2). Therefore, we have to complete (one run of) our experiment while much fewer than a 100 photons pass through the interferometer. The role of the super-detector will play a photodetector with noise of about one count per second. A student either puts or does not put this detector inside the interferometer. The output of the detector is connected to a bell. Our task is to find out if there is a detector without ringing the bell. We are allowed sometimes to fail, i.e. to ring the bell. Then we call the student to start everything from the beginning. But, when we claim that the detector is there, we must be right with high probability.

In order to achieve this goal we tune the Mach–Zehnder interferometer for maximal destructive interference in detector D_2, see figure 2. We prepare a weak source of light (low intensity laser) such that it sends about 10^3 photons/s. We add a fast electronic switch (time of operation $\tau = 10^{-6}$ s) which stops the beam when the detector D_2 absorbs a photon. (Detector D_1 does not play any role in the experiment, so we can omit it.)

The experiment runs as follows: we open the laser and measure after what time the detector switch stops the laser. If it happens after about a second we can safely claim that the detector is not there: the probability for a mistake is about 2^{-1000}. If, however, the time is about 10^{-3} s, we can claim that the detector is there: the probability for a mistake now is also not large, about 10^{-2}. If our device works properly, the only other probable outcome is that we will hear the bell first. If the detector is there, the probability for this is about $\frac{2}{3}$. In this case we have to call the student to start again. But the other third is, roughly, the probability for a successful interaction-free measurement. It seems that all kinds of noises which we have not taken into account cannot deny us a significant chance to perform this experiment successfully.

I believe that the proposed interaction-free measurement is more than just a demonstration of the peculiarities of quantum mechanics. This is a measurement which can be performed on an infinitely fragile object without disturbing it in any way whatsoever. I believe that it can have practical applications. Now let us discuss one of the possible applications: detecting an excited atom without changing its state.

Suppose we are going to investigate an exotic excited state which can be characterized by the ability to absorb a photon of certain energy. We want to know when an atom in such a state has appeared, but we do not want to change its state while detecting it. As far as we know, our method is the only one available. This is in contrast with the toy experiment above where we could always locate the detector using photons which it cannot detect.

In order to detect an atom we can use exactly the same system, with laser and fast electronic switch on the detector (figure 2). But we encounter a serious problem: the cross section of absorption of a photon by an atom is much smaller than the cross section of the laser beam. Thus, many photons will come through the interferometer before one of them will be absorbed by the atom. Even more photons will pass before the detector D_2 will click signalling the existence of the excited atom. When more than 100 photons pass the interferometer, we, most probably, will get a click just from noise, and therefore we will not be able to detect the atom, unless some procedure increasing the probability of the absorption will be found.

I have more hope in finding some other experimental implementations of interaction-free measurements. First, the Mach–Zehnder can be replaced by a Michelson–Morley interferometer, or any other two- (or several-) arm interferometer. But it can also be implemented in a single-beam interferometer with filters of polarization or some other degrees of freedom. Let me now state a general scheme for interaction-free measurements.

Our task is to detect a system in a certain state, say $|\Psi\rangle$. This state might cause some kind of 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. If we succeed in this task, we call the experiment an interaction-free measurement.

Let us assume that if the system is in a state $|\Psi\rangle$ and 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 measuring device is in a state $|\Phi_2\rangle$ (which is orthogonal to $|\Phi_1\rangle$) than neither the system nor the measuring device changes their state:

$$\begin{aligned}
&|\Psi\rangle|\Phi_1\rangle \to |\text{expl.}\rangle \\
&|\Psi_\perp\rangle|\Phi_1\rangle \to |\Psi_\perp\rangle|\Phi_1\rangle \\
&|\Psi\rangle|\Phi_2\rangle \to |\Psi\rangle|\Phi_2\rangle \\
&|\Psi_\perp\rangle|\Phi_2\rangle \to |\Psi_\perp\rangle|\Phi_2\rangle.
\end{aligned} \tag{1}$$

Now, let us start with an initial state of the measuring device

$$|\chi\rangle = \alpha|\Phi_1\rangle + \beta|\Phi_2\rangle. \tag{2}$$

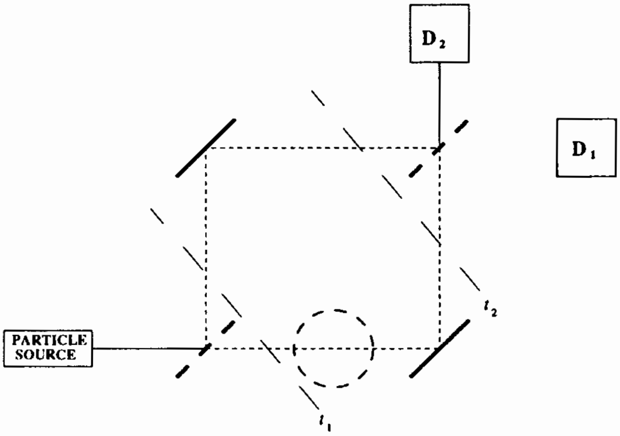

Figure 3. The photon passing through the interferometer and detected by D_2 can be considered as a measuring device prepared at time t_1 in the state $|\chi\rangle = (1/\sqrt{2})(|\Phi_1\rangle + |\Phi_2\rangle)$, and found at time t_2 in the state $|\chi_\perp\rangle = (1/\sqrt{2})(|\Phi_1\rangle - |\Phi_2\rangle)$.

If the initial state of the system is $|\Psi\rangle$, then the measurement interaction is:

$$|\Psi\rangle|\chi\rangle \to \alpha|\text{expl.}\rangle + \beta|\Psi\rangle|\Phi_2\rangle = \alpha|\text{expl.}\rangle + \beta|\Psi\rangle(\beta^*|\chi\rangle + \alpha|\chi_\perp\rangle) \tag{3}$$

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:

$$|\Psi_\perp\rangle|\chi\rangle \to |\Psi_\perp\rangle|\chi\rangle. \tag{4}$$

To complete our measuring procedure we perform a measurement of the measuring device which distinguishes between $|\chi\rangle$ and $|\chi_\perp\rangle$. Since there is no component with $|\chi_\perp\rangle$ in the final state (4), it can be obtained only if the initial state of the system was $|\Psi\rangle$. This is also the final state of the system: we do not obtain $|\chi_\perp\rangle$ in the case of the explosion. The probability to obtain $|\chi_\perp\rangle$ (if the system was initially in the state $|\Psi\rangle$) is $|\alpha\beta|^2$. It is less than the probability for explosion, which is $|\alpha|^2$, but it is finite, and the ratio $|\beta|^2$ can be made as close as we want to 1. In this case, the measurements will detect the state $|\Psi\rangle$ with probability $\frac{1}{2}$ (and with probability $\frac{1}{2}$ will be the explosion).

A Mach–Zehnder interferometer (figure 3) is a particular implementation of this scheme. Indeed, the photon entering the interferometer can be considered a measuring device prepared by the first beamsplitter in a state $|\chi\rangle = (1/\sqrt{2})(|\Phi_1\rangle + |\Phi_2\rangle)$ at time t_1, 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 $|\chi_\perp\rangle = (1/\sqrt{2})(|\Phi_1\rangle - |\Phi_2\rangle)$ at time t_2. Indeed, if the state $|\chi_\perp\rangle$ were measured at time t_2, it must be found with certainty.

The difficulties of splitting and reuniting beams in the Mach–Zehnder interferometer can be avoided if our system is in a state $|\Psi\rangle$ which is sensitive, say, to a left circular polarization of light: it causes some kind of explosion, while right polarization causes no change. Then we can start with an x-polarized photon which interacts with the system and look for a y-polarized photon. If we do find such photon, we know that the system is in the state $|\Psi\rangle$.

Our method has the remarkable property of not destroying infinitely fragile states and it is applicable to a wide class of physical systems. Therefore, although now we do not know where it can have practical applications, we are optimistic about finding such applications in the future.

After completing this manuscript I have learned that the proposed experiment is, in fact, in progress in Innsbruck [3]. Kwiat *et al* have developed a new scheme which employs the quantum Zeno effect in addition to the original idea. Their method allows detection of a super-detector which explodes when triggered, without exploding it, with probability arbitrarily close to 100%, while the best method we knew before reached only 50%. We will follow here their proposal and describe the conceptual scheme of their new method.

Again, the measuring device has two orthogonal states, $|\Phi_1\rangle$ and $|\Phi_2\rangle$, but now the free Hamiltonian of the measuring device is not zero, it causes a rotation in the Hilbert space of the above two states:

$$|\Phi(t)\rangle = \sin(\omega t)|\Phi_1\rangle + \cos(\omega t)|\Phi_2\rangle. \tag{5}$$

Instead of one interaction described by equation (1) we perform a dense set of instantaneous interactions (1) during the period of time $\pi/2\omega$. We perform N such interactions after each time $\pi/2\omega N$.

The experiment runs as follows. We start with the initial state of the measuring device $|\Phi(0)\rangle = |\Phi_2\rangle$. If there is no super-detector, i.e. if the initial state is $|\Psi_\perp\rangle$, the interactions (1) do not change the time evolution of the measuring device, and therefore the unitary evolution for the measuring procedure during the time $\pi/2\omega$ is

$$|\Psi_\perp\rangle|\Phi_2\rangle \rightarrow |\Psi_\perp\rangle|\Phi_1\rangle. \tag{6}$$

If, instead, the super-detector is present, i.e. if its initial state is $|\Psi\rangle$, then the interactions (1) 'freeze' the measuring device in the state $|\Phi_2\rangle$. The unitary transformation of the measuring procedure is now

$$|\Psi\rangle|\Phi_2\rangle \rightarrow \sin\left(\frac{\pi}{2N}\right)\sum_{k=1}^{N}\cos^{k-1}|\mathrm{expl.}_{(k)}\rangle + \cos^N\left(\frac{\pi}{2N}\right)|\Psi\rangle|\Phi_2\rangle \tag{7}$$

where $|\mathrm{expl.}_{(k)}\rangle$ is the state of the super-detector and the measuring device exploded at the time $k\pi/2\omega N$. We assume that the states $|\mathrm{expl.}_{(k)}\rangle$ corresponding to explosions at different times are orthogonal. Finally, at the time $\pi/2\omega$, we perform a measurement which distinguishes between the states $|\Phi_1\rangle$ and $|\Phi_2\rangle$. This completes the measuring procedure: the state $|\Phi_2\rangle$ can be found only if the place is not empty. For N large, the probability for an explosion goes to 0, and the probability for detection of the super-mine without exploding it goes to 1 (since $\cos^N(\pi/2N) \rightarrow 1$).

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