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HOW TO DETECT AN EXCITED ATOM without disturbing it *or* HOW TO LOCATE A SUPER-MINE without exploding it

Lev Vaidman
School of Physics and Astronomy
Tel–Aviv University, Tel–Aviv 69978 ISRAEL

Abstract

Possible realistic implementations of a method for interaction-free measurements, due to Elitzur and Vaidman, are proposed and discussed. It is argued that the effect can be easily demonstrated in an optical laboratory.

1 How to locate a Super-Mine

A "Super-mine" is a device which explodes if *anything* touches it. Proton, electron, photon, neutrino,... anything that reaches the mine, with any energy, triggers an explosion. Our task is to locate the mine. We have to find out where it *is*, not where it was. We have to check that the mine is in a certain location without exploding it. We have no any additional information, except that there is nothing else except mines in the region. We are allowed to fail in our procedure, i.e. to explode a mine. In that case we can try again, in another region. But our measurement has to be reliable: we must not be mistaken when we say that there is a mine.

The task seems to be impossible: the mine interacts with the external world only by explosion when it is "touched," so how it can be found without an explosion? In classical physics this task is certainly impossible, since its solution leads to a paradox: to find the mine you have to touch it, but if you touch it, it explodes. Nevertheless, quantum mechanics allows a simple solution, which was suggested recently by Elitzur and myself [1].

Our method is based on a particle interferometer analogous to the Mach-Zehnder interferometer used in classical optics. In principle, it can work with any type of particle. The particle reaches the first beam splitter 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 beam splitter (Fig. 1*a*). Two detectors collect the particles after they pass through the second beam splitter. We can arrange the positions of the beam splitters 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 region of space where we want to detect the existence of a mine (Fig. 2*b*). We send a single particle through the system. There are three possible outcomes of this measurement:

i) no detector clicks, ii) detector D_1 clicks, iii) detector D_2 clicks.

In the first case, the particle explodes the mine. The probability for this outcome 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 mine is, and when the mine is not located in one of the arms of the interferometer. In this case there has been no interaction with the object, so we can try again. 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 there is a mine inside the interferometer without exploding it. If we wish to specify by the interaction-free procedure the exact position of the mine inside the interferometer, we can test (locally) that except for that region, the interferometer is empty.

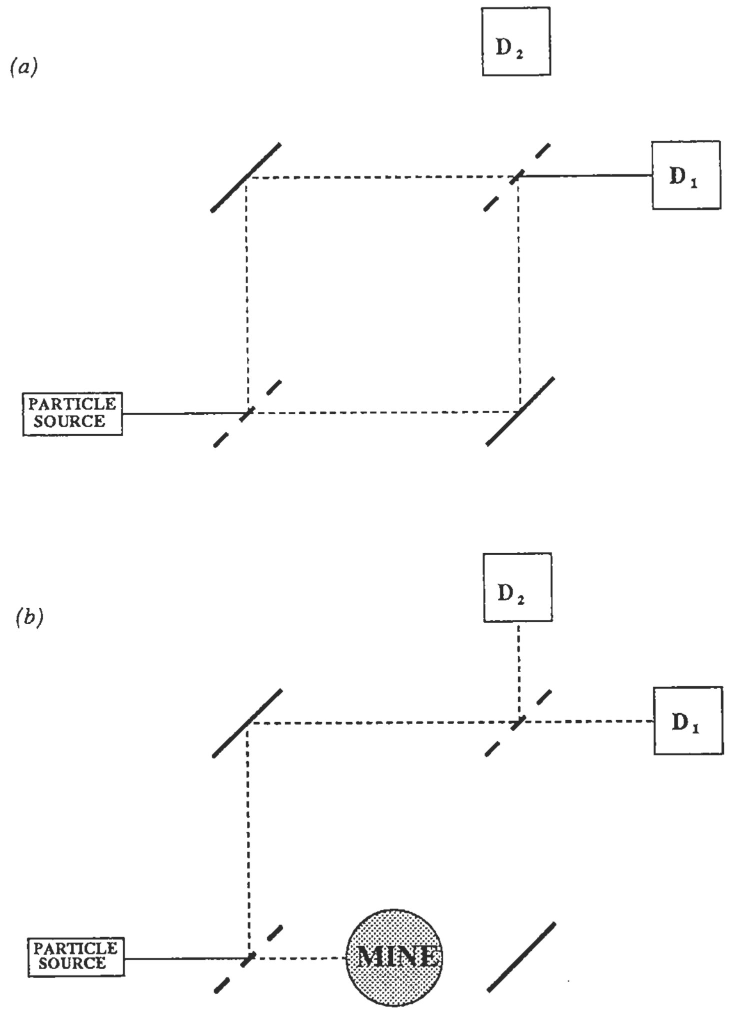

FIG. 1. (a) If there is no any object inside the interferometer, D_2 never clicks. (b). When D_2 clicks after sending just one particle we know that the mine is inside the interferometer and it is still intact.

2 What is the Probability for a Successful Experiment?

Even the ideal experiment does not always succeed. We have seen that the probability for success here is only 1/4. But we also have the probability 1/4 not to destroy the mine without finding it. Trying again and again, until success or an explosion, leads to the probability 1/3 of locating the mine without an explosion. We have shown [1] that by modifying the transmission coefficients of the beam splitters in the interferometer we can obtain (almost) the probability 1/2 for success.

This is, however, a gedanken experiment. A super-mine which is sensitive to everything, 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-mine. The mine can be replaced by a fragile object which is nevertheless stable in the environment of the laboratory. It "explodes" (or clicks) if a photon with a certain energy hits it. Our task now is to detect the object without exploding it, using only such photons.

We do not need a source of single photons. We assume that the explosion (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 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.)

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, then the photon which hits the object does not have to *invariably* explode it. 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 no object inside the interferometer. Also, we will get wrong clicks due to noise in the detector D_2.

What I have understood from my interaction with experimentalists [2] is that 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). This is the most important limitation on the proposed "interaction-free" measurement. The most optimistic estimate I heard [3] was the ratio of 1:1000. Therefore, we have to complete (one run of) our experiment while much fewer than a 1000 photons pass through the interferometer.

3 A Game

Consider a boy trying to catch a girl in a dark room. In order to catch her, he has to know where she is. But if she knows that she has been located, she has enough time to move to another location. She constantly looks in all direction, and any time she sees a photon, she moves. The girl can detect any photons the boy uses. Then, classically, the task of the boy is hopeless. However, quantum mechanics allows the boy to locate the girl without her being aware of, and thus, to catch her.

Let us now discuss a proposal for demonstration of such game in a laboratory. Instead of the girl we will take a high efficiency photo-detector. As I understand [4] there are detectors of up to 70% efficiency with noise of about one count per second. A student either puts or does not put this detector inside the interferometer. (Or, more realistically, she blocks or does not block the arm of the interferometer with a small mirror such that the reflected photons are absorbed by the photo-detector.) 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 correct with high probability.

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

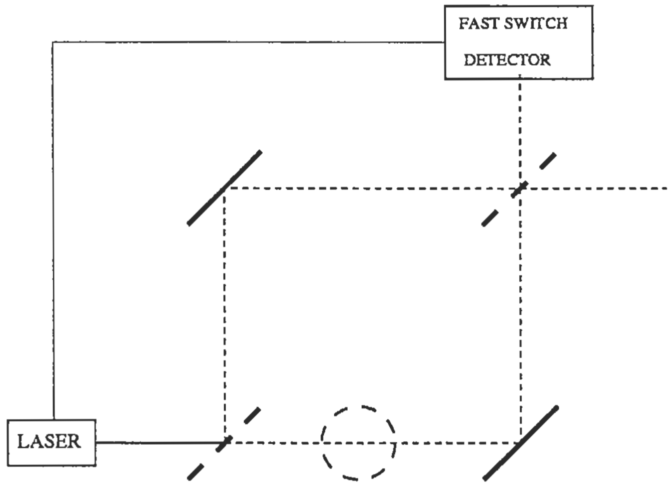

FIG. 2. A fast switch detector stops the beam when it detects a photon. We can learn about the existence of an object inside the interferometer by measuring the time it takes for the detector to click starting from the beginning of the run.

The experiment runs as follows: we switch on 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 the mistake is about 2^{-1000}. If, however, the time is about 10^{-3}sec we can claim that the detector is there: the probability for a mistake now is also not large, about 10^{-3}. 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 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 kind of noises which we have not taken into account cannot deny us a significant chance to perform this experiment successfully. If we are satisfied by a less reliable measurement (even 10% error is a sound experiment) we even do not need an extraordinarily precise Mach-Zehnder interferometer or ultrasensitive detectors.

4 How to Detect an Excited Atom

I believe that the proposed interaction-free measurement is more than just a demonstration of 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 application: 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 of previous section where we always could 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 (Fig. 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 click of detector D_2 signaling the existence of the excited atom. When more than 1000 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. I am not familiar enough with the experimental possibilities, but there is hope of finding some focusing (squeezing ?) procedure to improve the ratio between the cross section for absorption and the cross section of the beam.

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.

5 Generalization of Interaction-Free Measurement

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:

$$\begin{aligned} |\Psi\rangle\ \ |\Phi_1\rangle &\rightarrow |explosion\rangle \\ |\Psi_\perp\rangle|\Phi_1\rangle &\rightarrow |\Psi_\perp\rangle|\Phi_1\rangle \\ |\Psi\rangle\ \ |\Phi_2\rangle &\rightarrow |\Psi\rangle\ \ |\Phi_2\rangle \\ |\Psi_\perp\rangle|\Phi_2\rangle &\rightarrow |\Psi_\perp\rangle|\Phi_2\rangle. \end{aligned} \tag{1}$$

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

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

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

$$|\Psi\rangle|\chi\rangle \rightarrow \alpha|explosion\rangle + \beta|\Psi\rangle|\Phi_2\rangle = \alpha|explosion\rangle + \beta|\Psi\rangle(\beta^*|\chi\rangle + \alpha|\chi_\perp\rangle), \tag{3}$$

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:

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

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 1/2 (and with probability 1/2 will be the explosion).

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

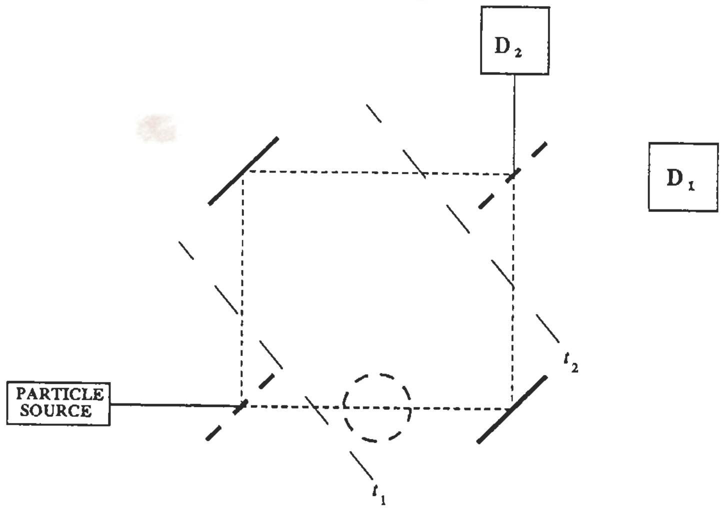

FIG. 3. The photon passing through the interferometer and detected by D_2 can be considered as a measuring device prepared at time t_1 in the state $|\chi\rangle = \frac{1}{\sqrt{2}}(|\Phi_1\rangle + |\Phi_2\rangle)$, and found at time t_2 in the state $|\chi_\perp\rangle = \frac{1}{\sqrt{2}}(|\Phi_1\rangle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

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 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.

6 Acknowledgements

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