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IS IT POSSIBLE TO KNOW ABOUT SOMETHING WITHOUT EVER INTERACTING WITH IT?

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We shall describe a measurement which, when successful, is capable of ascertaining the existence of an object in a given region of space, although no particle and no light has "touched" this object. This is a new type of an interaction-free quantum measurement (Elitzur and Vaidman 1991) which has no classical analog.

Let us begin with a brief review of nonlocal measurements which yield information about the existence of an object in a given region of space. If an object is charged or has an electric (magnetic) moments, then its existence in a given region can be inferred without any particle passing through that region, but rather by the measurement of the electric (magnetic) field the object creates outside the region. Quantum mechanics allows inferring the existence of an object in a nonlocal way via Aharonov-Bohm effect even when the object creates no electromagnetic field outside a certain space region, but only an electromagnetic potential. Even if the object creates no detectable change at a distance, i.e. it interacts with the external world only locally, its location can often be found in a simple nonlocal interaction-free measurement (i.e., without interacting with the object). For example, assume it is known that an object is located in one out of two boxes. Looking and *not* finding it in one box tells us that the object is located inside the other box. What allowed us to infer that an object is located in a given place was the information about the object prior to the measurement. The question we address here is this: Is it possible to obtain knowledge about the existence of an object in a certain place using interaction-free measurements *without any prior information* about the object? The answer is, indeed, in the affirmative as we proceed to show.

Our method is based on a particle interferometer which is analogous to the Mach-Zehnder interferometer of classical optics. In principle, it can work with any type of particles. A particle reaches the first beam splitter which has the transmission coefficient $\frac{1}{2}$. The transmitted and reflected parts of the particle's wave are then reflected by the mirrors in such a way that they are reunited at another, similar beam splitter (Fig. 1). 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 so that, due to the destructive interference, no particles are detected by one of the detectors, say D_2 (but all are detected by D_1). If, without changing the positions of the mirrors and the beam splitters, we block one of the two arms of the interferometer, the particles which succeeded to pass through the interferometer are detected with equal probability by both detectors D_1 and D_2. Thus, detector D_2 detects particles only if one of the routes of the interferometer is blocked.

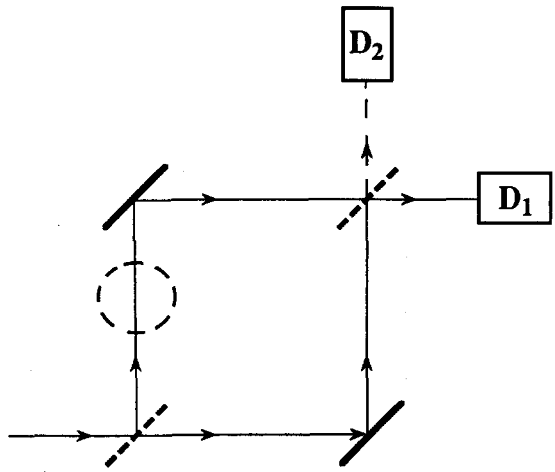

Fig.1 Mach-Zehnder type particle interferometer. Detector D_2 clicks only if one of the arms of the interferometer is blocked by an object.

A practical realization of such an interferometer with electrons and protons is hampered by strong electromagnetic interaction with the environment, but neutron interferometers operate in many laboratories. However, our method requires a *single particle interferometer*, i.e. an interferometer with one particle passing through it at a time, and there is no appropriate neutron source which produces a single particle states. Recently (Grangier et all 1986) experiments were performed with a source of single photon states. Thus we propose to use the Mach-Zehnder interferometer with such a source of single photons.

Our procedure for finding out about the existence of an object in a given place, without passing even one photon through it, is then as follows: We arrange a photon interferometer as described above, i.e. no photons are detected by D_2 when both routes of the interferometer are open, and position it in such a way that one of the routes of the photon passes through the region of space where we want to detect the existence of an object (Fig. 1). We send a single photon 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 photon has been absorbed (or scattered) by the object and never reached the detectors. The probability for this outcome is $\frac{1}{2}$. In the second case (the probability for which is $\frac{1}{4}$) , the measurement has not succeeded either. The photon could have reached D_1 in both cases: when the object is, and when the object 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 an object inside the interferometer without having "touched" the object. Indeed, we saw that the necessary condition for D_2 to detect a photon is that one of the routes of the interferometer is closed; therefore the object must be there. This is an interaction-free measurement because we had only one photon and, has it interacted with the object, it could never reach detector D_2.

The quantum mechanical formalism describing the operation of our device is simple. Let us designate the state of the photon moving to the right by $|1\rangle$, and the state of the photon moving up by $|2\rangle$. In a model which illustrates the essential aspects of the procedure, every time a photon is reflected the phase of its wave function changes by $\frac{\pi}{2}$. Thus, the operation of the half-silvered plate on the state of the photon is

$$|1\rangle \rightarrow \frac{1}{\sqrt{2}}[|1\rangle + i|2\rangle], \qquad |2\rangle \rightarrow \frac{1}{\sqrt{2}}[|2\rangle + i|1\rangle]. \tag{1}$$

The operations of the two fully-silvered mirrors are described by

$$|1\rangle \rightarrow i|2\rangle, \quad \text{and} \quad |2\rangle \rightarrow i|1\rangle. \tag{2}$$

If the object is absent, i.e. we have a standard (undisturbed) photon interferometer, the evolution of the photon's state is described by:

$$|1\rangle \rightarrow \frac{1}{\sqrt{2}}[|1\rangle + i|2\rangle] \rightarrow \frac{1}{\sqrt{2}}[i|2\rangle - |1\rangle] \rightarrow \frac{1}{2}[i|2\rangle - |1\rangle] - \frac{1}{2}[|1\rangle + i|2\rangle] = -|1\rangle. \tag{3}$$

The photon, therefore, leaves the interferometer moving to the right towards detector D_1, which then clicks. If, however, the object is present, the evolution is described by:

$$|1\rangle \rightarrow \frac{1}{\sqrt{2}}[|1\rangle + i|2\rangle] \rightarrow \frac{1}{\sqrt{2}}[i|2\rangle + i|scattered\rangle] \rightarrow \frac{1}{2}[i|2\rangle - |1\rangle] + \frac{i}{\sqrt{2}}|scattered\rangle, \tag{4}$$

where $|scattered\rangle$ is the state of the photon scattered by the object. According to the standard approach to quantum measurement, the detectors cause the collapse of the quantum state (4):

$$\frac{1}{2}[i|2\rangle - |1\rangle] + \frac{i}{\sqrt{2}}|scattered\rangle \rightarrow \begin{cases} |2\rangle, & D_2 \text{ clicks, probability } \frac{1}{4}, \\ |1\rangle, & D_1 \text{ clicks, probability } \frac{1}{4}, \\ |scattered\rangle & \text{no clicks, probability } \frac{1}{2}. \end{cases} \tag{5}$$

We see that the photon can be detected by detector D_2 only if the object is present. Thus, the click of the detector D_2 yields the desired information, namely, that the object is located somewhere along the arms the interferometer. If we wish to specify by the interaction-free procedure an exact position of the object inside the interferometer, we can test (locally) that all but that region inside the interferometer is empty.

The information about the existence of the object was obtained without "touching" it. Indeed, we had a single photon. Had it been scattered or absorbed (i.e. "touched") by the object it would not be detected by D_2. Our procedure is, therefore, an interaction-free measurement of the existence of the object.

The argument which claims that this is an interaction-free measurement sounds very persuasive, but is, in fact, an artifact of a certain interpretation of quantum mechanics. The paradox of obtaining information without interaction appears due to the assumption that only one "branch" of a quantum state exists. This paradox can be avoided in the framework of the Many-Worlds Interpretation (MWI) which, however, has paradoxical features of its own. In the MWI there is no collapse and all "branches" of the photon's state (5) are real. These three branches correspond to three different "worlds". In one world the photon is scattered by the object and in two others it does not. Since all worlds take place in the physical universe we cannot say that nothing has "touched" the object. We get information about the object without touching it in one world but we "pay" the price of interacting with the object in the other world.

Our idea is most dramatically illustrated in a way which is free from any specific interpretation of quantum theory and any specific meaning of the words "interaction-free", "without touching", etc. Consider a stock of bombs with a sensor of a new type: if a single photon hits the sensor, the bomb explodes. Suppose further that some of the bombs in the stock are out of order: the sensor is missing so that photons pass through the hole without being affected in any way, and the bomb does not explode. Is it possible to find out bombs which are still in order?

Of course, we can direct some light at each bomb. If it does not explode it is not good. If it does, it *was* good. But we are interested in finding a good bomb without destroying it. The trouble is that the bomb is designed in such a way that *any* interaction with light, even a very soft photon bouncing on bomb's sensor, causes an explosion. The task therefore seems to be impossible, and in classical physics it surely is. However, our interaction-free quantum measurement yields a solution.

We place a bomb in such a way that its sensor is located in one of the possible routes of the photon inside the interferometer. We send photons one by one through the interferometer until either the bomb explodes or detector D_2 detects the photon. If neither of the above happens, we stop the experiment after a large number of photons have passed the interferometer. In the latter case we can conclude that this given bomb is not good, and we shall try another one. If the bomb is good and exploded, we shall also start all over again with the next bomb. If, however, D_2 clicks, then we achieved what we promised: we know that this bomb is good and we did not explode it.

The probability for such a success is $p = \frac{1}{4}$. By repeating our procedure in cases D_1 has clicked, the probability increases to $p = \frac{1}{3}$. We have showed (Elitzur and Vaidman 1991) that by an appropriate modification one can reach $p = \frac{1}{2}$.

In one respect the experiment which tests a bomb without exploding it is easier than the experiment of testing the existence of an object in a given place without touching it. For the latter, in order to ensure that we indeed do not touch the object, we need a single-particle interferometer. We could deduce that no photon scattered by the object because there was only one photon and had it been scattered by the object it would not be detected by D_2. For the experiment with the bomb, however, the source of single particle states is not necessary. We know that no photon had touched it simply by the fact that it did not explode. A weak enough source, which is stopped once detector D_2 clicks, serves our purpose. Even the probability of finding a good bomb remains the same: in the optimal regime, about one half of the good bombs are tested without being destroyed.

Our method allows to detect the existence of any unstable system without disturbing its internal quantum state. It might, therefore, have practical applications. For example, one might select atoms in a specific excited metastable state. Let us assume that the atom has very high crossection for absorbing photons of certain energy while it is in one out of several metastable states into which it can be "pumped" by a laser, and that the atom is practically transparent for these photons when it is not in this state. Then, our procedure selects atoms in the specific state without changing their state in any way. Some other applications of our idea have been proposed recently (for example, Hardy 1992, Cufaro-Petroni and Vigier 1992).

It is common to think that unlike classical mechanics, quantum mechanics poses severe restrictions on the minimal disturbance of the system due to the measurement procedure. We, however, have presented here an ultimately delicate quantum measurement which is impossible to perform classically. We found that it is possible to obtain certain information about a region in space without any interaction in that region neither in the past nor at present.

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