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QUANTUM INFORMATION AND QUANTUM MEASUREMENTS

Are Interaction-Free Measurements Interaction Free?[1]

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Abstract—In 1993, Elitzur and Vaidman introduced the concept of interaction-free measurements, which allowed finding objects without "touching" them. In the proposed method, since the objects were not touched, even by photons, thus, the interaction-free measurements can be called "seeing in the dark." Since then, several experiments have been successfully performed and various modifications were suggested. Recently, however, the validity of the term "interaction-free" has been questioned. The criticism of the name is briefly reviewed and the meaning of the interaction-free measurements is clarified. © *2001 MAIK "Nauka/Interperiodica".*

INTRODUCTION

The interaction-free measurements proposed by Elitzur and Vaidman [1, 2] (EV IFM) led to numerous investigations and several experiments have been performed [3–9]. While there is a consensus about the importance of this proposal, there have been several objections to the name "interaction-free." Some authors, in trying to avoid it, made modifications such as "interaction (energy exchange) free measurements" [10, 11], "indirect measurements" [12], "seemingly interaction-free measurements" [13], "interaction-free" interrogation [8], etc. Moreover, recently, Simon and Platzman [14] claimed that there is a "fundamental limit on 'interaction-free' measurements."

The discussion of the term "interaction-free" appears in the original IFM paper [2], but reading papers about the interaction-free measurements has convinced me that the concept of the EV IFM has been frequently misunderstood. In this paper, I want to clarify in which sense the interaction-free measurements are interaction free. I will also make a comparison with procedures termed "interaction-free measurements" in the past and will analyze conceptual advantages and disadvantages of various modern schemes for the interaction-free measurements.

HOW THE EV IFM PAPER WAS WRITTEN

At the beginning of 1991, Avshalom Elitzur came to me with the following question: "Suppose there is an object such that any interaction with it leads to an explosion. Can we locate the object without exploding it?" Our joint work resulted in a positive answer to this question described in the EV IFM paper.

Presented in this way, the name interaction-free is clearly appropriate. Simple logic tells us: given that any interaction leads to an explosion and given that there has been no explosion, it follows that there has been no interaction. This way of reasoning was described in Section 4 of our paper. However, the proposed method has certain additional features, which justify the name "interaction-free." The method is applicable for the location of objects, which do not necessarily explode. Even for such objects we can claim that, in a sense, the finding of its location is interaction-free. These aspects of interaction-free measurements were explained at the beginning of the EV IFM paper. Before I continue with the discussion, let me briefly describe our solution to the posed question.

THE ORIGINAL PROPOSAL FOR THE IFM

Our method is based on the Mach-Zehnder interferometer. A photon (from a source of single photons) reaches the first beam splitter, which has the transmission coefficient 1/2. The transmitted and reflected parts of the photon wave are then reflected by the mirrors and finally reunite at another, similar beam splitter (Fig. 1a). Two detectors are positioned to detect the photon after it passes through the second beam splitter. We arrange the positions of the beam splitters and the mirrors such that (because of destructive interference) the photon is never detected by one of the detectors, say D_2, and is always detected by D_1. We then position the interferometer in such a way that one of the routes of the photon passes through the place where the object (a bomb) might be present (Fig. 1b). We send a single photon through the system. There are three possible outcomes of this measurement: (i) explosion, (ii) detector D_1 clicks, or (iii) detector D_2 clicks.

If the detector D_2 clicks (the probability for that is 1/4), we have achieved our goal: we know that the object is inside the interferometer and it did not explode.

[1] This article was submitted by the author in English.

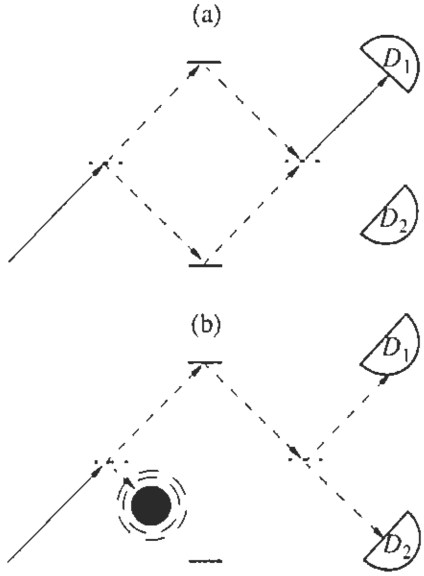

Fig. 1. (a) When the interferometer is properly tuned, all photons are detected by D_1 and none reach D_2. The mirrors must be rather massive and have well-defined positions. (b) If the bomb is present, detector D_2 has a 25% probability of detecting the photon that we send through the interferometer, and, in this case, we know that the bomb is inside the interferometer without exploding it.

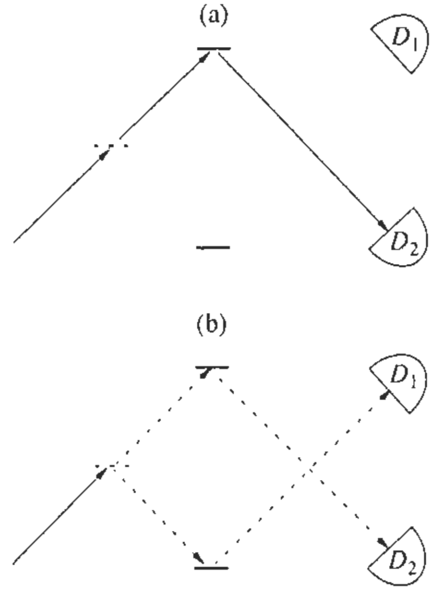

Fig. 2. (a) The "trajectory" of the photon in the Wheeler experiment, given that D_2 detected the photon as usually described. The photon cannot leave any physical trace outside its trajectory. (b) The trajectory of the quantum wave of the photon in the Wheeler experiment according to the von Neumann approach. The photon remains in a superposition until the collapse, which takes place when one of the wave packets reaches a detector.

MEASUREMENT WITHOUT "TOUCHING"

In the IFM paper, we have claimed that, in a sense, we locate the object without touching it. However, we wrote: "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 interpretation that is usually adopted in discussions of the Wheeler delayed-choice experiment). The paradox of obtaining information without interaction appears due to the assumption that only one 'branch' of a quantum state exists" ([2], p. 991).

One of the "choices" of the Wheeler delayed-choice experiment is an experiment with a Mach-Zehnder interferometer in which the second beam splitter is missing (see Fig. 2). In the course of the experiment with a single photon detected by D_2, it is usually accepted that the photon had a well-defined trajectory: the upper arm of the interferometer. In contrast, according to the von Neumann approach, the photon was in a superposition inside the interferometer until the time when one part of the superposition reached the detector D_2 (or until the time that the other part reached the detector D_1, if that event was earlier). At that moment, the wave function of the photon collapses to the vicinity of D_2. The justification of the Wheeler claim that the photon detected by D_2 never was in the lower arm of the interferometer is that, according to the quantum mechanical laws, we cannot see any physical trace from the photon in the lower arm of the interferometer. This is true if (as it happened to be in this experiment) the photon from the lower arm of the interferometer cannot reach the detector D_2. The fact that there cannot be a physical trace of the photon in the lower arm of the interferometer can be explained within the framework of the two-state vector formulation of quantum mechanics [15, 16]. This formalism is particularly suitable for this case, because we have a pre- and post-selected situation; the photon was post-selected at D_2. Thus, while the wave function of the photon evolving forward in time does not vanish in the lower arm of the interferometer, the backward-evolving wave function does. The vanishing of one of the waves (forward or backward) at a particular location is enough to ensure that the photon cannot cause any change in the local variables of the lower arm of the interferometer.

In our experiment, we have the same situation. If there is an object in the lower arm of the interferometer, the photon cannot go through this arm to the detector D_1. This is correct if the object is such that it explodes whenever the photon reaches its location and we have not observed the explosion. Moreover, this is also correct in the case in which the object is not completely transparent and it blocks the photon in the lower arm, eliminating any possibility of reaching D_1. Even in this case, we can claim that we locate the object "without touching it." This claim is identical to the argument according to which the photon in the Wheeler experiment went solely through the upper arm. In the framework of the two-state vector approach, we can say that the forward-evolving quantum state is nonzero in the lower arm of the interferometer up to the location of the object, while the backward-evolving wave function is nonzero from the location of the object. Thus, at every point of the lower arm of the interferometer one of the quantum states vanishes. This ensures that the photon cannot make any physical trace there. Note, that the two-state vector formalism itself does not suggest that the photon is not present at the lower arm of the interferometer; it only helps to establish that the photon does not leave a trace there. The latter is the basis for the statement that, in a sense, the photon was not there.

NESTED INTERACTION-FREE MEASUREMENTS

There is a very puzzling point regarding the interaction-free localization of a quantum object, which can itself be in a superposition of being in different locations. Our method works well for this case too (see Section 3 of the IFM paper). If D_2 clicks, the object is localized inside the interferometer. If we assume that before the experiment, the whole volume of the interferometer, except the "working area," which we want to test, was found empty, we can claim that the click of D_2 localizes the object inside the working area. We can safely make this claim because we are sure that any test of our statement will invariably show that we are right. The object, if observed, will certainly be found in the working area.

Surprisingly, however, the click of D_2 is not enough to claim that the photon was not in the lower arm. Indeed, the object could itself be a "particle" of another interaction-free measurement (we can consider a gedanken situation in which the object, which explodes when the photon reaches its location can, nevertheless, be manipulated by other means). If the latter was successful (i.e., its "D_2" clicked) the other observer can claim that he localized the single photon of the first experiment in the working area, i.e., that the photon passed through the lower arm of the interferometer on its way to D_2 [17]. Paradoxically, both claims are true: the first experiment localizes the object in the working area; and the second, at the same time, localizes the single photon there. Both claims are true separately, but not together: if we would try to locate both the photon and the object in the working area, we will fail with certainty. Such peculiarities take place because we consider a pre- and post-selected situation (the post-selection is that in both experiments detectors D_2 click) [18]. In spite of this peculiar feature, the experiment is still interaction-free in the above sense; if we locate an object in a particular place, we can claim that no photon was in the vicinity of this place.

THE IFM OF RENNINGER AND DICKE AND THE EV IFM

In the many papers describing the experiments and modifications of the EV IFM, the first cited papers are one by Renninger [19] and another by Dicke [20]. It is frequently claimed that Elitzur and Vaidman "extended the ideas of Renninger and Dicke," and Geszti [21] even wrote that we just "amplified the argument by inventing an efficient interferometric setup." In fact, we came to the idea of the IFM without any connection to these papers (the first was translated for me only recently). We do cite the Dicke's paper, although, what we got from it is just the name: "interaction-free measurements" but not the method, and, more importantly, the Dicke's paper does not address the question we have solved. It seems to me, that there is very little in common between the Renninger–Dicke IFM and the EV IFM.

Renninger considered the spherical wave of a photon after it extended beyond the radius at which a scintillation detector was located in the part of the space angle (see Fig. 3). He discussed a *negative result experiment*: a situation in which the detector does not detect anything. The state of the detector remained unchanged, but, nevertheless, the wave-function of the photon is modified. Dicke considered an atom in a ground state inside a potential well. Half of the well was illuminated by a beam of photons. Again, a negative result experiment was considered in which no scattered photons were observed. Dicke concentrated on the question of the conservation of energy in this experiment. The atom changed its state from the ground state to a superposition in which the atom does not occupy the half that is well illuminated by the photons, while photons did not change their state at all, and he asked: "What is the source of the additional energy of the atom?!"

The word "measurement" in quantum theory has many very different meanings [22]. The purpose of the Renninger and Dicke measurements is the *preparation* of a quantum state. In contrast, the purpose of the EV interaction-free measurement is to obtain *information* about the object. In Renninger and Dicke measurements, the *measuring device* is undisturbed (these are negative result experiments), while in the EV measurement, the *observed object* is, in some sense, undisturbed. In fact, in general EV IFM, the quantum state of the observed object is disturbed: the wave function becomes localized at the vicinity of the lower arm of the interferometer (see Section 3 of the EV paper). The reasons for using the term interaction-free measurements are that the object does not explode (if it is a bomb), it does not absorb any photon (if it is an opaque object), and that we can claim that, in a sense, the photon does not reach the vicinity of the object.

A variation of the Dicke measurement, which can serve as the measurement of the location of an object, was considered in the original paper for justifying the name interaction-free measurements of the EV procedure. An object in a superposition of being in two far away places was considered. A beam of light passed through one of the locations and no scattered photons were observed. We obtain information that the object is located in the other place. This experiment is interaction-free because the object (if it is a bomb) would not explode: the object is found in the place where there were no photons. In such an experiment, however, it is more difficult to claim that the photon was not in the vicinity of the object: the photon was not in the vicinity of the *future* location of the object. But the main weakness of this experiment, relative to the EV scheme, is that we get information about the location of the object only if we have *prior information* about the state of the object. If it is known in advance that the object can be found in one of two boxes, and it was not found in one, obviously, we then know that it is in the second box. The whole strength of the EV method is that we get information that an object is inside the box *without any prior information*! The latter, contrary to the former task, cannot be done without the help of a quantum theory.

Note that Dicke named his experiment "interaction-free" because of another reason: the photons did not scatter making this a "negative result experiment." By using the same term, we, ourselves, caused this confusion.

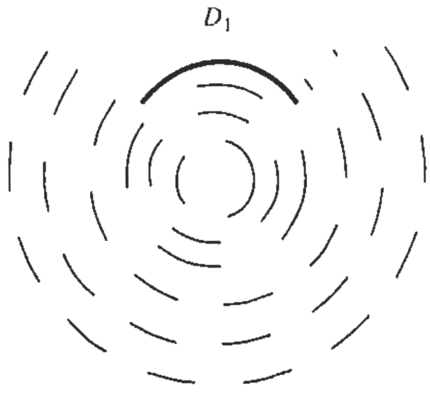

Fig. 3. Renninger experiment. The photon spherical wave is modified by the scintillation detector D_1, in spite of the fact that it detected nothing.

THE NONDEMOLITION MEASUREMENTS, ENERGY-EXCHANGE FREE, MOMENTUM-EXCHANGE FREE MEASUREMENTS, AND THE EV IFM

A basic concept of quantum measurement theory is a *nondemolition measurement*. The nondemolition measurement of a variable *A* leaves the quantum state of the object undisturbed provided it was in an eigenstate of *A* prior to the measurement. It is not an easy task to perform a nondemolition measurement [23]. The EV method can be applied for performing various nondemolition measurements [11]. Indeed, even if the measurement interaction can destroy the object, the method also allows measurement without disturbing the object. The EV interaction-free measurement is a nondemolition measurement of the position of an object (more precisely, the measurement of the projection operator in a certain region). However, no nondemolition measurement of the position of the object is an interaction-free measurement. There are methods of nondemolition measurements in which, in the process of measurement, the state of the object changes, but these changes are compensated for at the end of the process [24]. Such measurements should not be considered as interaction-free measurements.

Probably, the largest misconception about the IFM is defining them as momentum-exchange free measurements [14]. The EV IFM can localize a bomb in an arbitrarily small region without exploding it, even if the quantum state of the bomb was spread out initially. The localization of an object without uncertain change in its momentum leads to an immediate contradiction with the Heisenberg uncertainty principle. Identifying the interaction-free measurements as momentum-exchange free measurements, Simon and Platzman derived "fundamental limits" on the IFM. They argued that the IFM can be performed only on an infinitely sensitive bomb and that a bomb, which is infinitely sensitive to any momentum transfer, cannot be placed in the vicinity of the IFM device from the beginning. These arguments fail because the EV IFM are not defined as momentum-exchange free measurements. (Probably, the misconception arose because of the frequent mention of Dicke's paper, which concentrated on the issue of momentum exchange in his procedure.)

The arguments, similar to those of Simon and Platzman are relevant for performing a modification of the EV IFM proposed by Penrose [25]. In the Penrose version of IFM, the bomb plays the role of one mirror of the interferometer. Thus, indeed, the uncertainty principle put limits on placing the bomb in its place before the experiment [26]. In contrast, in the EV IFM, the bomb need not be localized prior to the measurement: the IFM localizes it by itself.

The ideal EV IFM need not be a momentum-exchange free experiment, but it might be. If the object is localized before the IFM procedure, then, indeed, the expectation value of any power of momentum of the object and the momentum distribution of the photon inside the interferometer do not change during the time of the "interaction" between the photon and the object (The time when the interaction could take place or the time when the interaction took place in another branch of the Universe).

Aharonov [27] pointed out that the IFM process cannot take place without the exchange of some physical variable. In the EV procedure, there is an exchange of *modular momentum*. The collapse of the quantum wave of the photon from the superposition of the two wave packets separated by a distance a to a single wave packet continuing to move in the upper part of the interferometer is accompanied by the change in the *momentum modulo $\hbar/a$*. Note that the distribution of modular momentum for the object (provided it was localized at the lower arm of the interferometer from the beginning) does not change, but the distribution is such that the *momentum modulo $\hbar/a$* is completely uncertain, and this prevents contradiction with the conservation law for the total modular momentum.

THE ALMOST 100% EFFICIENT IFM

In the IFM paper, we found a modification of the scheme presented above, which allows detection of almost 50% of the bombs without explosion (the rest explode in the process). At that point, my belief in the many-worlds interpretation (MWI) led us to a mistake: I persuaded Avshalom Elitzur that we cannot do better. We wrote a footnote: "The MWI also presents a natural explanation for why we cannot do better. Consider the world in which the photon hits the bomb. The world that replaces it, in the case where the bomb is transparent, interferes destructively with the world in which the detector D_2 clicks. Since the latter is completely eliminated, it cannot have a probability larger than that of the former."

There is nothing wrong with the MWI. I made a mistake in the framework of the MWI. I had not realized that one can devise an experiment in which there are many different worlds in which the photon hits the bomb (the hits take place at different times). All these worlds should interfere destructively with the world in which D_2 clicks. For this, it is necessary that the sum of the amplitudes of the worlds with the explosion will compensate for the amplitude of the world in which the bomb is detected without an explosion. If there is a large number of "explosion" worlds, then the total measure of the existence of the worlds with explosions [28], i.e., the probability of explosion, can be arbitrarily small even when the sum of the amplitudes is large.

Our mistake was corrected by Kwiat *et al.* [3]. They applied the quantum Zeno effect for constructing the IFM scheme, which, in principle, can be made arbitrarily close to 100% efficiency. The experiment with theoretical efficiency higher than 50% has been performed [7].

I believe another claim about the IFM based on the reasoning in the framework of the MWI [29] is correct. It is impossible to make an interaction-free measurement telling us that in a certain place there is no any object. Here, I mean "interaction-free" in the sense that no photons (or other particles) pass through the place in question. The argument is that our physical laws, which include only local interactions, make getting information about some location without any particle being there paradoxical. In the case of the bomb, the MWI solves the paradox by saying that since the laws apply to the whole physical universe, which includes all the worlds, the reasoning must be true only when we consider all the worlds. Since there are worlds with the explosion, we cannot say, on the level of the physical Universe, that no photons were at the location of the bomb. In contrast, when there is no bomb, there are no other worlds. The paradox in our world becomes the paradox for the whole universe, which is a real paradox.

MODIFICATIONS OF THE EV IFM

The almost 100% efficient scheme of Kwiat *et al.* [3] can be described as follows: Two identical optical cavities coupled through a highly reflective mirror. A single photon originally placed in the left cavity. If the right cavity is empty, then after the particular number N of reflections, the photon will certainly be in the right cavity. If, however, there is a bomb in the right cavity, the photon with the probability close to 1 for large N will be found in the left cavity. Testing, at the appropriate time, for the photon in the left cavity will tell us if there is the bomb in the right cavity.

This method keeps all conceptual features of the EV IFM. If the photon is found in the left cavity, we are certain that there is an object in the right cavity. If the object is an ultrasensitive bomb or if it is a completely nontransparent object, which does not reflect light backwards (e.g., it is a mirror rotated by 45° relative to the optical axes of the cavity as in the Kwiat *et al.* experiment), then, when we detect the photon in the left cavity, we can claim that it never "touched" the object in the same sense as is true in the original EV method.

Another modification of the EV IFM, which leads to almost 100% efficiency has been proposed by Paul and Pavicic [30] and implemented in the laboratory by Tsegaye *et al.* [6]. The advantage of this proposal is that it has just one cavity and is, therefore, easier to perform. The basic ingredient of this method is an optical resonance cavity, which is almost transparent when empty, and is an almost perfect mirror when there is an object inside. However, this method has a small conceptual drawback. There is always a nonzero probability of reflecting the photon even if the cavity is empty. Thus, detecting the reflected photon cannot ensure the presence of the object with 100% certainty. This drawback has only academic significance. In any real experiment, there will be uncertainty anyway, and the uncertainty I mentioned can always be reduced below the level of the experimental noise.

Other modifications of the IFM are related to interaction-free "imaging" [8] and interaction-free measurements of semitransparent objects [31, 32]. These experiments hardly pass the strict definition of the IFM in the sense that the photons do not pass in the vicinity of the object. However, they all achieve a very important practical goal since we "see" the object significantly reducing the irradiation of the object: this can allow measurements on fragile objects.

CONCLUSIONS

I have reviewed various analyses, proposals, and experiments, which appeared following the method for the interaction-free measurement of Elitzur and Vaidman. The common feature of all these proposals is that we obtain information about an object while significantly reducing the irradiation of the objects. The meaning of the EV IFM is that if an object changes its internal state (not the quantum state of its center of mass) due to the radiation, then the method allows the detection of the location of the object without *any* change in its internal state. IFM allows the measurement of the position of infinitely fragile objects. In a sense, it locates objects without "touching," i.e., without particles of any kind passing through its vicinity. Contrary to recent claims, such IFM do not have any fundamental limit.

We should mention that interaction-free measurements do not have a vanishing interaction Hamiltonian. In general, the IFM are also not energy-exchange free or momentum-exchange free processes: the IFM can significantly change the quantum state of the observed object and we still call it interaction-free. On the other hand, the method allows the performing of some nondemolition measurements. It might be momentum-exchange free and energy-exchange free.

The numerous papers on the IFM interpreted the concept of interaction-free in many different ways. I hope that in this paper, I clarified the differences and unambiguously stated the meaning of the original proposal.

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