The Meaning of the Interaction-Free Measurements

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Interaction-free measurements introduced by Elitzur and Vaidman [Found. Phys. **23**, 987 (1993)] allow finding infinitely fragile objects without destroying them. Many experiments have been successfully performed showing that indeed, the original scheme and its modifications lead to reduction of the disturbance of the observed systems. However, there is a controversy about the validity of the term "interaction-free" for these experiments. Broad variety of such experiments are reviewed and the meaning of the interaction-free measurements is clarified.

I. INTRODUCTION

The interaction-free measurements proposed by Elitzur and Vaidman [1,2] (EV IFM) led to numerous investigations and several experiments have been performed [3–12]. One of the possible applications of the interaction-free measurements for quantum communication is that it opens up the way to novel quantum non-demolition techniques [13,14]. Other applications are using the idea of interaction-free measurements for "interaction-free" computation [15] and for improving cryptographic schemes [16,17]. However, 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" [18,13], "indirect measurements" [19], "seemingly interaction-free measurements" [20], "interaction-free" interrogation [9,11], "exposure-free imaging" [21], "interaction-free interaction" [22], "absorption-free measurements" [23], etc. Moreover, Simon and Platzman [24] claimed that there is a "fundamental limit on 'interaction-free' measurements". In many works on the implementation and the analysis of the EV IFM there is a considerable confusion about the meaning of the term "interaction-free". For example, a very recent paper [14] stated that "energy exchange free" is now well established as a more precise way to characterize IFM in the case of classical objects. On the other hand, Ryff and Ribeiro [25] used the name "interaction-free" for a very different experiment. 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 IFM.

The plan of this paper is as follows: in Section II I will describe the original proposal of Elitzur and Vaidman. Section III is devoted to a particular aspect of the IFM according to which the measurement is performed without any particle being at the vicinity of the measured object. The discussion relies on the analogy with the "delayed choice experiment" proposed by Wheeler [26]. In Section IV I make a comparative analysis of the "interaction-free measurements" by Renninger and Dicke. In Section V I analyze interaction-free measurements of quantum objects. Section VI devoted to the controversy related to the momentum and energy transfer in the process of the IFM. In Section VII I discuss modifications of the original EV proposal, in particular, the application of the quantum Zeno effect for obtaining a more efficient IFM. I end the paper with a few concluding remarks in Section VIII.

II. THE ELITZUR-VAIDMAN INTERACTION-FREE MEASUREMENTS

In the EV IFM paper the following question has been considered:

> Suppose there is an object such that *any* interaction with it leads to an explosion. Can we locate the object without exploding it?

The EV method is based on the Mach-Zehnder interferometer. A photon (from a source of single photons) reaches the first beam splitter which has a transmission coefficient $\frac{1}{2}$. The transmitted and reflected parts of the photon wave are then reflected by the mirrors and finally reunite at another, similar beam splitter, see Fig. 1*a*. Two detectors are positioned to detect the photon after it passes through the second beam splitter. The positions of the beam splitters and the mirrors are arranged in such a way 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.

This interferometer is placed in such a way that one of the routes of the photon passes through the place where the object (an ultra-sensitive bomb) might be present (Fig. 1*b*). A single photon passes through the system. There are three possible outcomes of this measurement: i) explosion, ii) detector D_1 clicks, iii) detector D_2 clicks. If detector D_2 clicks (the probability for that is $\frac{1}{4}$), the goal is achieved: we know that the object is inside the interferometer and it did not explode.

The EV method solves the problem which was stated above. It allows finding with certainty an infinitely sensitive bomb without exploding it. The bomb might explode in the process, but there is at least a probability of 25% to find the bomb without the explosion. "Certainty" means that when the process is successful (D_2 clicks), we know for sure that there is something inside the interferometer.

The formal scheme of the EV method is as follows. The first stage of the process (the first beam splitter) splits the wave packet of the test particle into superposition of two wave-packets. Let us signify $|\Phi_{\rm int}\rangle$ is the wave packet which goes through the interaction region and $|\Phi_{\rm free}\rangle$ is the wave packet which does not enter the interaction region. In the basic EV procedure the first stage is

$$|\Phi\rangle \rightarrow \frac{1}{\sqrt{2}}(|\Phi_{\rm int}\rangle + |\Phi_{\rm free}\rangle). \qquad (1)$$

The next stage is the interaction between the object (the bomb) and the test particle. If the test particle enters the interaction region when the bomb is present, it causes an explosion:

$$|\Phi_{\rm int}\rangle|\text{bomb in}\rangle \rightarrow |\text{explosion}\rangle. \qquad (2)$$

If the test particle does not enter the interaction region or if the bomb is not present, then nothing happens at this stage:

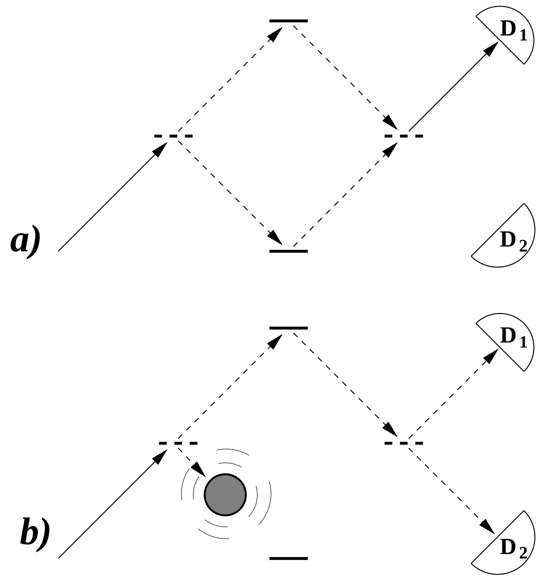

FIG. 1. (a) When the interferometer is properly tuned, all photons are detected by D_1 and none reach D_2.
(b) If the bomb is present, detector D_2 has the probability 25% to detect the photon sent through the interferometer, and in this case we know that the bomb is inside the interferometer without exploding it.

$$\begin{aligned} |\Phi_{\rm free}\rangle|\text{bomb in}\rangle &\rightarrow |\Phi_{\rm free}\rangle|\text{bomb in}\rangle, \\ |\Phi_{\rm int}\rangle|\text{bomb out}\rangle &\rightarrow |\Phi_{\rm int}\rangle|\text{bomb out}\rangle, \\ |\Phi_{\rm free}\rangle|\text{bomb out}\rangle &\rightarrow |\Phi_{\rm free}\rangle|\text{bomb out}\rangle. \end{aligned} \qquad (3)$$

The next stage is the observation of the interference between the two wave packets of the test particle; it takes place at the second beam-splitter and detectors. It is achieved by splitting the noninteracting wave packet

$$|\Phi_{\rm free}\rangle \rightarrow \frac{1}{\sqrt{2}}(|\Phi_1\rangle + |\Phi_2\rangle), \qquad (4)$$

and splitting the wave packet which passed through the interaction region (if it did)

$$|\Phi_{\rm int}\rangle \rightarrow \frac{1}{\sqrt{2}}(|\Phi_1\rangle - |\Phi_2\rangle). \qquad (5)$$

The observation of the test particle is described by

$$\begin{aligned} |\Phi_1\rangle|D_1 \text{ ready}\rangle|D_2 \text{ ready}\rangle &\rightarrow |\Phi_1\rangle|D_1 \text{ clicks}\rangle|D_2 \text{ ready}\rangle, \\ |\Phi_2\rangle|D_1 \text{ ready}\rangle|D_2 \text{ ready}\rangle &\rightarrow |\Phi_2\rangle|D_1 \text{ ready}\rangle|D_2 \text{ clicks}\rangle. \end{aligned} \qquad (6)$$

The state $|D_2 \text{ clicks}\rangle$ corresponds to the success of the experiment, when we know that the bomb is present in the interaction region; we signify it by the state $|\text{know bomb in}\rangle$.

If the bomb is not present then the the EV measurement is described by

$$\begin{aligned} &|\Phi\rangle|\text{bomb out}\rangle|D_1 \text{ ready}\rangle|D_2 \text{ ready}\rangle \rightarrow \\ &|\Phi_1\rangle|\text{bomb out}\rangle|D_1 \text{ clicks}\rangle|D_2 \text{ ready}\rangle. \end{aligned} \qquad (7)$$

If the bomb is inside the interferometer, then the the EV measurement is described by

$$\begin{aligned} &|\Phi\rangle|\text{bomb in}\rangle|D_1 \text{ ready}\rangle|D_2 \text{ ready}\rangle \rightarrow \\ &\frac{1}{\sqrt{2}}|\text{explosion}\rangle + \frac{1}{2}|\text{know bomb in}\rangle \\ &+\frac{1}{2}|\Phi_1\rangle|\text{bomb in}\rangle|D_1 \text{ clicks}\rangle|D_2 \text{ ready}\rangle. \end{aligned} \qquad (8)$$

The experiment ends up in finding the bomb with the probability of 25%, explosion with the probability of 50%, and no information but no explosion with the probability of 25%. In the latter case we can repeat the procedure and in this way (by repeating again and again) we can find one third of bombs without exploding them. It was found [2] that changing the reflectivity of the beam splitters can improve the method such that the fraction of the bombs remaining intact almost reaches one half.

III. MEASUREMENT WITHOUT "TOUCHING"

The name "interaction-free" seems very appropriate for a procedure which allows finding objects without exploding them, in spite of the fact that these objects explode due to *any* interaction. 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 argument which sounds unambiguous in the framework of classical physics requires careful definition of the meaning of "any interaction" in the domain of quantum mechanics.

The weakness of the definition: "The IFM is a procedure which allows finding an object exploding due to *any* interaction without exploding it," is that quantum mechanics precludes existence of such objects. Indeed, a good model for an "explosion" is an inelastic scattering [27]. The Optical Theorem [28] tells us that there cannot be an inelastic scattering without some elastic scattering. The latter does not change the internal state of the object, i.e., the object does not explode. In order to avoid non-existing concepts in the definition of the IFM, we should modify the definition in the following way:

> The IFM is a procedure which allows finding (at least sometimes) bombs of any sensitivity without exploding them.

The method presented in the EV IFM paper have certain additional features which further justify the name "interaction-free". The method is applicable for finding the location of objects which do not necessarily explode. Even for such an object we can claim that, in some sense, finding its location is "interaction-free". The discussion about the justification of the term "interaction-free" for the EV procedure has started in the original EV IFM paper [2]:

> 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 Wheeler's delayed-choice experiment). The paradox of obtaining information without interaction appears due to the assumption that only one "branch" of a quantum state exists. (p. 991)

One of the "choices" of Wheeler's delayed-choice experiment is an experiment with a Mach-Zehnder interferometer in which the second beam splitter is missing (see Fig. 2). In the run 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 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 Wheeler's 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 in the framework of the two-state vector formulation of quantum mechanics [29,30]. This formalism is particularly suitable for this case because we have pre- and post-selected situation: the photon was post-selected at D_2. 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. Vanishing 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.

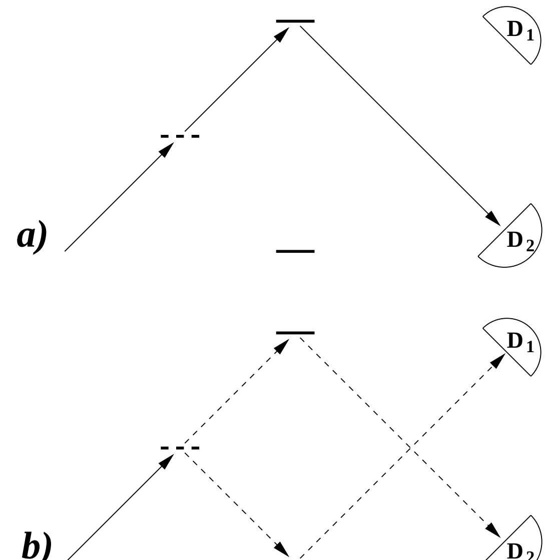

FIG. 2. (a) The "trajectory" of the photon in the Wheeler experiment given that D_2 detected the photon, as it is usually described. The photon cannot leave any physical trace outside its "trajectory".
(b) The "trajectory" of the quantum wave of the photon in the Wheeler experiment according to the von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

In our experiment (Fig. 1.) 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, but moreover, this is also correct in the case in which the object is completely nontransparent 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". This claim is identical to the argument according to which the photon in Wheeler's 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 only up to the location of the object, while the backward-evolving wave function is nonzero only from the location of the object. Thus, at every point of the lower arm of the interferometer one of the quantum states vanishes. The two-state vector formalism 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 claim that, in some sense, the photon was not there.

IV. THE IFM OF RENNINGER AND DICKE

In many papers describing experiments and modifications of the EV IFM the first cited papers are one by Renninger [31] and another by Dicke [32]. It is frequently claimed that Elitzur and Vaidman "extended ideas of Renninger and Dicke" or just "amplified the argument by inventing an efficient interferometric set" [27]. In fact, there is little in common between Renninger-Dicke IFM and the EV IFM. Dicke's paper is cited in the EV IFM paper, but the citation is given only for the justification of the name: "interaction-free measurements". Renninger's and Dicke's papers do not have the method, and, more importantly, they do not address the question which the EV IFM paper have solved.

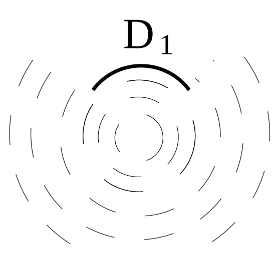

FIG. 3. Renninger's experiment. The photon spherical wave is modified by the scintillation detector D_1 in spite of the fact that it detects nothing.

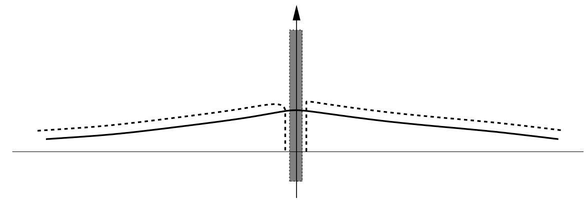

FIG. 4. Dicke's Experiment. The ground state of a particle in the potential well (solid line) is changed to a more energetic state (dashed line) due to short radiation pulse, while the quantum state of the photons in the pulse remains unchanged.

Renninger discussed a *negative result experiment*: a situation in which the detector does not detect anything. In spite of the fact that nothing happened to the detector, there is a change in the measured system. He considered a spherical wave of a photon after it extended beyond the radius at which a scintillation detector was located in part of the solid angle, see Fig. 3. The state of the detector remained unchanged but, nevertheless, the wave-function of the photon is modified. The name "interaction-free" for Renninger's setup might be justified because there is not *any*, not even an infinitesimally small, change in the state of the detector in the described process. This is contrary to the classical physics in which interaction in a measurement process can be made arbitrary small, but it cannot be exactly zero.

Dicke considered the paradox of the apparent nonconservation of energy in a Renninger-type experiment. He considered an atom in a ground state inside a potential well. Part of the well was illuminated by a beam of photons. A negative result experiment was considered in which no scattered photons were observed, see Fig. 4. The atom changed its state from the ground state to some superposition of energy eigenstates (with a larger expectation value of energy) in which the atom does not occupy the part of the well illuminated by the photons. The photons, however, apparently have not changed their state at all. Then, Dicke asked: "What is the source of the additional energy of the atom?!"

Careful analysis [33,34] (in part, made by Dicke himself) shows that there is no real paradox with the conservation of energy, although there are many interesting aspects in the process of an ideal measurement [35]. One of the key arguments is that the photon pulse has to be well localized in time and, therefore, it must have a large uncertainty in energy.

The word "measurement" in quantum theory have many very different meanings [36]. The purpose of the Renninger and Dicke measurements is *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 Sec. 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 some sense, the photon does not reach the vicinity of the object.

A variation of Dicke's measurement which can serve as a measurement of the location of an object was considered in the EV IFM 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. This yields the information that the object is located in the other place. The described 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 at the vicinity of the object: the photon was not at 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, then obviously, we 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 help of a quantum theory.

In order to see the difference more vividly let us consider an application of the EV method to Dicke's experimental setup. Instead of the light pulse we send a "half photon": We arrange the EV device such that one arm of the Mach-Zehnder interferometer passes through the location of the particle, see Fig. 5. Then, if detector D_2 clicks, the particle is localized in the interaction region.

In both cases (the Renninger-Dicke IFM and this EV IFM) there is a change in the quantum state of the particle without, in some sense, interaction with the photon. However, the situations are quite different. In the original Dicke's experiment we can claim that the dashed line of Fig. 4. is the state of the particle after the experiment only if we have prior information about the state of the particle before the experiment (solid line of Fig. 4.) In contrast, in the EV modification of the experiment, we can claim that a particle is localized in the vicinity of the interaction region (dashed line of Fig. 5.) even if we had no prior information about the state of the particle.

It seems that Dicke named his experiment "interaction-free" mainly because the photons did not scatter: this is a "negative result experiment". In the EV experiment the photon clearly changes its state and it is essential that it was detected: this is not a "negative result experiment" in this sense.

Paul [37] noted that there is an earlier paper by Renninger [38] in which an experimental setup almost identical to that of the EV IFM was considered: a Mach-Zehnder interferometer tuned to have a dark output towards one of the detectors. However, Renninger never regarded his experiment as a measurement on an object which was inside the interferometer: Renninger's argument, as in the experiment described in Fig. 3, was about "interaction-free" changing the state of the photon. Renninger has not asked the key question of the EV IFM: How to get information in an interaction-free manner?

I can see something in common between the Renninger-Dicke IFM and the EV IFM in the framework of the many-worlds interpretation. In both cases there is an "interaction": radiation of the scintillator in the Renninger experiment or explosion of the bomb in the EV experiment, but these interactions take place in the "other" branch, not in the branch we end up discussing the experiment. In an attempt to avoid adopting the many-worlds interpretation such interactions were considered as *counterfactual* [39,40].

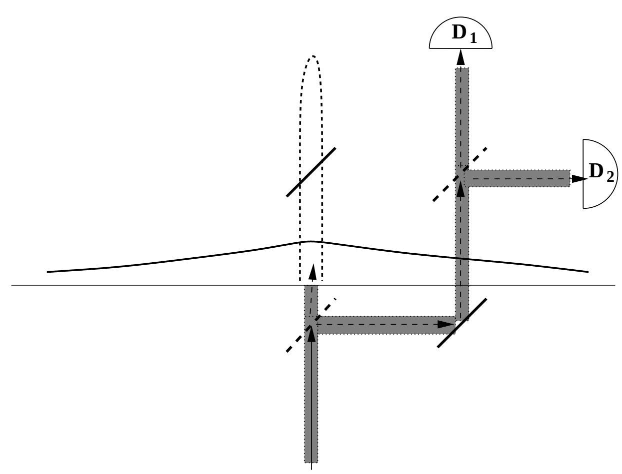

FIG. 5. The EV modification of Dicke's Experiment. The ground state of a particle in the potential well (solid line) is changed to a well localized state (dashed line) when the photon is detected by the detector D_2.

V. INTERACTION-FREE LOCALIZATION OF A QUANTUM OBJECT

We name the experiment described in Fig. 5. "interaction-free" measurement (cf. "interaction-free collapse" of the EV IFM paper) in spite of the fact that both the particle and the photon change their states. The main motivation for the name is that the interaction between the particle and the photon is such that there is an "explosion" if they "touch" each other, but the experiment (when D_2 clicks) ends up without explosion.

The second aspect of the EV IFM, when applied to quantum objects, encounters a subtle difficulty. After performing the procedure of the IFM and obtaining the photon click at D_2, we cannot claim that the photon was not present at the region of interaction; moreover, it might be the case that, in some sense, the photon was there *with certainty.*

First, let us repeat the argument which led us to think that the photon was not there. Consider again the experiment described on Fig. 1., but now the "bomb" is replaced by a quantum object in a superposition of being in the "interaction region" and somewhere else outside the interferometer. If D_2 clicks, we can argue that the object had to be on the way of the photon in the lower arm of the interferometer, otherwise, it seems that we cannot explain the arrival of the photon to the "dark" detector D_2. If the object was on the way of the photon, we can argue that the photon was not there, otherwise we had to see the explosion. Therefore, the photon went through the upper arm of the interferometer and it was not present in the interaction region.

The persuasive argument of the previous paragraph is incorrect! Not just the semantic point discussed above, i.e., that according to the standard approach the quantum wave of the photon in the lower arm of the interferometer was not zero until it reached the interaction region. It is wrong to say that the photon was not in the lower arm even in the part *beyond* the interaction region. In the experiment in which D_2 clicks, the photon *can* be found in any point of the lower arm of the interferometer!

This claim can be seen most clearly by considering "nested interaction-free measurements" [41]. The object is in a superposition of two wave packets inside its own Mach-Zehnder interferometer (see Fig. 6.) If D_2 (for the photon) clicks, the object is localized inside the interaction region W. However, the object itself is the test particle of another IFM (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 this other IFM is successful (i.e. "D_2" for the object clicks) then the other observer can claim that she localized the photon of the first experiment at W, i.e. that the photon passed through the lower arm of the interferometer on its way to D_2.

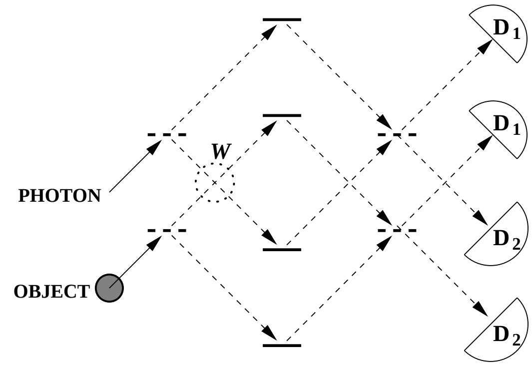

FIG. 6. Hardy's Paradox. Two interferometers are tuned in such a way that, if they operate separately, there is a complete destructive interference towards detectors D_2. The lower arm of the photon interferometer intersects the upper arm of the object interferometer in W such that the object and the photon cannot cross each other. When the photon and the object are sent together (they reach W at the same time) then there is a nonzero probability for clicks of both detectors D_2. In this case one can infer that the object was localized at W and also that the photon was localized at W. However, the photon and the object were not present in W together. This apparently paradoxical situation does not lead to a real contradiction because all these claims are valid only if tested separately.

Paradoxically, all these claims are true (in the operational sense): if we look for the photon in W, we find it with certainty; if we look, instead, for the object in W, we find it with certainty too. Both claims are true separately, but not together: if we look for the pair, the photon and the object together, in W, we 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) [42]. An interesting insight about this peculiar situation can be learned through the analysis of the *weak measurements* performed on the object and the photon inside their interferometers [43].

In spite of this peculiar feature, the experiment is still interaction-free in the following sense. If somebody would test the success of our experiment for localization of the object, i.e. would measure the location of the object shortly after the "meeting time" between the object and the photon, then we know with certainty that she would find the object in W and, therefore, the photon cannot be there. Discussing the issue of the presence of the object with her, we can correctly claim that in our experiment the photon was not in the vicinity of the object. Indeed, given the assumption that she found the object, we know that she has not seen the photon in the lower arm of the interferometer, even if she looked for it there. However, if, instead of measuring the position of the object after the meeting time, she finds the object in a particular superposition (the superposition which with certainty reaches D_2), she can claim with certainty that the photon was in W. (Compare this with *deterministic quantum interference experiments* [44]).

VI. MOMENTUM AND ENERGY TRANSFER IN THE IFM

Probably, the largest misconception about the IFM is defining them as momentum and energy exchange-free measurements [18,13,24]. The EV IFM can localize a bomb in an arbitrary small region without exploding it even if the quantum state of the bomb was spread out initially. Localization of an object without uncertain change in its momentum leads to immediate contradiction with the Heisenberg uncertainty principle. Identifying the interaction-free measurements as momentum-exchange free measurements, Simon and Platzman [24] derived "fundamental limits" on the IFM. They argued that the IFM can be performed only on infinitely sensitive bomb and that a bomb which is infinitely sensitive to any momentum transfer could not 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 came because of frequent mentioning of Dicke's paper [32] which concentrated on the issue of the energy exchange in his IFM.)

The arguments, similar to those of Simon and Platzman might be relevant for performing a modification of the EV IFM proposed by Penrose [39]. He proposed a method for testing some property of an object without interaction. The object is again a bomb which explodes when anything, even a single photon, "touches" its trigger device. Some of the bombs are "duds": their trigger device is locked to a body of the bomb and no explosion and no relative motion of the trigger device would happen when it is "touched". Again, the paradox is that any touching of a trigger of a good bomb leads to an explosion, but, nevertheless, good bombs can be found (at least sometimes) without the explosion.

In the Penrose version of IFM, the bomb plays the role of one mirror of the interferometer, see Fig. 7. It has to be placed in the correct position. We are allowed to do so by holding the body of the bomb. However, the uncertainty principle puts limits on placing the bomb in its place before the experiment [45]. Only if the position of the bomb (in fact, what matters is the position of the dud) is known exactly, the limitations are not present. In contrast, in the EV IFM the bomb need not be localized prior to the measurement: the IFM localizes it by itself.

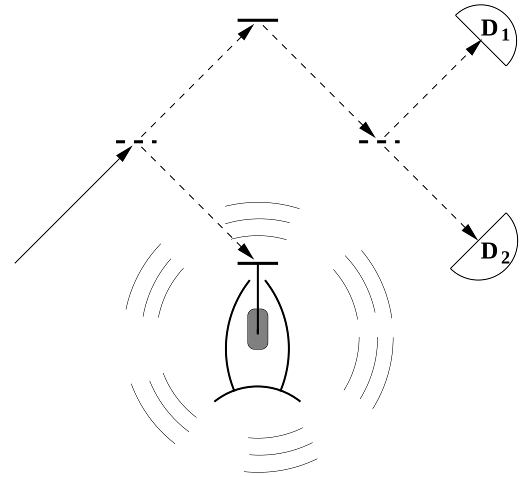

FIG. 7. The Penrose bomb-testing device. The mirror of the good bomb cannot reflect the photon, since the incoming photon causes an explosion. Therefore, D_2 sometimes clicks. The mirror of a dud is connected to the massive body, and therefore the interferometer "works", i.e. D_2 never clicks when the mirror is a dud.

The zero change in the momentum of the object, location of which is found in the IFM, is not a necessary condition for the measurement to be IFM, but there are IFM in which there is no change of the momentum of the object. Indeed, if the object has been localized before the IFM procedure, then its state and, therefore, its momentum distribution do not change during the process.

The relevant issue seems to be the change in the momentum of the observed object, but it is interesting to consider also the change in the momentum of the measuring device, thus analyzing the question of the *exchange* of the momentum. If the object is localized from the beginning then its state does not change, but the state of the photon does change: from the superposition of being in two arms of the interferometer it collapses into a localized wave packet in one arm of the interferometer. It can be arranged that the two separate wave packets of the photon have the same distribution of momentum. Then, the collapse to one wave packet will not change expectation value of any power of momentum of the photon.

Aharonov [47] has pointed out that although in this process there is no exchange of momentum in the above sense, still there is an exchange of certain 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 is accompanied by the change in the modular momentum $p_{phot} \mathrm{mod} \frac{\hbar}{a}$. The modular momentum of the object localized at the lower arm of the interferometer from the beginning, $p_{obj} \mathrm{mod} \frac{\hbar}{a}$, does not change (there is no *any* change in the quantum state of the object). One can, nevertheless, consider an exchange of modular momentum in this process: since $p_{obj} \mathrm{mod} \frac{\hbar}{a}$ is completely uncertain, there is no contradiction with the conservation law for the total modular momentum.

Note that the situation in which the expectation values of any power of momentum remains unchanged, while expectation values of powers of modular momentum change, is also a feature of Aharonov-Bohm type effects in which the quantum state changes even though no local forces are acting.

The method of the EV IFM can be applied for performing various non-demolition measurements [13]. Indeed, even if the measurement interaction can destroy the object, the method allows measurement without disturbing the object. However, not *any* non-demolition measurement is an IFM in the sense I discussed it here. In some nondemolition experiments the test particle of the measuring device explicitly passes through the location of the measured object. In other experiments the state of the object changes, but these changes are compensated at the end of the process [46]. I suggest that such measurements should not be considered as interaction-free.

VII. MODIFICATIONS OF THE EV IFM

The optimal scheme presented in the IFM paper allows detection of almost 50% of the bombs without explosion (the rest explode in the process). Kwiat *et al.* [3] applied quantum Zeno effect for constructing the IFM scheme which, in principle, can be made arbitrary close to the 100% efficiency. The experiment with theoretical efficiency higher than 50% has been performed [7].

The almost 100% efficient scheme of Kwiat *et al.* [3] can be explained as follows. The experimental setup consists of two identical optical cavities coupled through a highly reflective mirror, see Fig. 8. A single photon initially placed in the left cavity. If the right cavity is empty, then, after a particular number N of reflections, the photon with certainty will 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 a 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 ultra-sensitive bomb or if it is completely non-transparent object which does not reflect light backwards (e.g., it is a mirror rotated by 45 degrees 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 it is true in the original EV method.

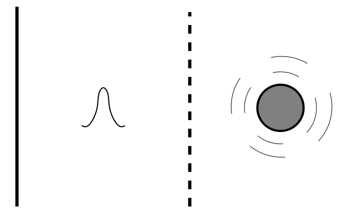

FIG. 8. The almost 100% efficient scheme of the IFM. If there is a "bomb" or a nontransparent object in the right cavity, then the photon stays in the left cavity, with a probability to go to the right cavity which can be made arbitrary small by increasing the reflectivity of the mirror between the cavities. If, however, the right cavity is empty, then after some time the photon will move there with certainty.

Another modification of the EV IFM which leads to the efficiency of almost 100% has been proposed by Paul and Pavičić [48] and implemented in a laboratory by Tsegaye *et al.* [6]. 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. The advantage of the proposal of Paul and Pavičić is that it has just one cavity, and is easier to perform. In fact, this method has been recently applied for "exposure-free imaging" of a two-dimensional object [21]. However, one cavity method has a conceptual drawback. In this experiment there is always a nonzero probability to reflect the photon even if the cavity is empty. Thus, detecting reflected photon cannot ensure presence of the object with 100% certainty. Essentially, this drawback has only an academic significance. In any real experiment there will be uncertainty anyway, and the uncertainty which I mentioned can be always reduced below the level of the experimental noise.

Other modifications of the IFM are related to interaction-free "imaging" [9] and interaction-free measurements of semi-transparent objects [49,23]. 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 reducing very significantly the irradiation of the object: this can allow measurements on fragile objects. Indeed, in spite of the fact that for distinguishing small differences in the transparency of an object the method is not very effective [50,51], it still can be useful for reduced irradiation pattern recognition [52].

Reasoning in the framework of the many-worlds interpretation (MWI) [53] leads to the statement that while we can find an object in the interaction-free manner, we cannot find out that a certain place is empty in the interaction-free way. Here, I mean "interaction-free" in the sense that no photons (or other particles) pass through the place in question. Getting information about some location in space without any particle being there is paradoxical because physical laws include only local interactions. In the case of finding the bomb, the MWI solves the paradox. Indeed, the laws apply to the whole physical Universe which includes all the worlds and, therefore, 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. Thus, it is impossible to find a procedure which tests the presence of an object in a particular place such that no particles visit the place both in the case the object is there and in the case the object is not there. Quantitative analysis of the limitations due to this effect were recently performed by Reif who called the task "interaction-free sensing" [54]. This effect also leads to limitations on the efficiency of "interaction-free computation" when all possible outcomes are considered [40].

VIII. CONCLUSIONS

I have reviewed various analyses, proposals, and experiments of IFM and measurements based on the EV IFM method. The common feature of these proposals is that we obtain information about an object while significantly reducing its irradiation.

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 detection of the location of the object without *any* change in its internal state. There is no any fundamental limit on such IFM. The IFM allow measurements of position of infinitely fragile objects. In some sense it locates objects without "touching", i.e. without particles of any kind passing through its vicinity. I have clarified the limited validity of this feature for IFM performed on quantum objects.

Numerous papers on the IFM interpreted the concept of "interaction-free" in many different ways. I hope that in this work I clarified the differences and stated unambiguously the meaning of the original proposal.

ACKNOWLEDGMENTS

It is a pleasure to thank Yakir Aharonov, Berge Englert, and Philip Pearle for helpful discussions. This research was supported in part by grant 471/98 of the Basic Research Foundation (administered by the Israel Academy of Sciences and Humanities) and the EPSRC grant GR/N33058.

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