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BRIEF REPORT

Setup for interaction-free measurement of multiple objects using single quantum probe

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Abstract
A theoretical setup is presented that extends quantum interaction-free measurement to include multiple objects. This is done by chaining and overlapping multiple single-object quantum interaction-free measurement devices so that the output of the device measuring the first object becomes the input of the device measuring the second object. The state of the system of classical objects (bits) is encoded into spatial or temporal degrees of freedom of the quantum probe. Different setup variations and applications are discussed.

1 Introduction

Interaction Free Measurement (further in the text IFM) is rooted in the early works on interpretations of the negative results of an experiment within the framework of quantum mechanics. Renninger [1] was one of the first to realize the power of non-detection in the context of quantum mechanics. He theorized that non-detection of a quantum object leads to the partial collapse of its wavefunction.

He proposed an arrangement in which an atom that is about to decay by emitting an alpha particle is surrounded by a spherical shell made of two half-spheres that are able to detect the alpha particle. Assuming the detectors are 100% efficient and given the spherical wavefunction of the particle, non-observation of the particle on one of the shells means it is definitely detected by the other. Moreover, if the shells are of different radius and are placed at different distances from the atom, so that they would still enclose the full wavefunction, but one of them would be able to interact with the wavefunction earlier than the other; the non-interaction of the closer shell with the particle (i.e. absence of the detection event on the closer shell at the time it should have happened), would effectively collapse the wavefunction to only a half-sphere. Hence, due to the binary nature of a quantum measurement (i.e. when measured, the particle can either "be there" or "not be there"), the event of non-detection can be exploited in order to obtain information about the object.

This observation was further developed by Elitzur and Vaidman [2]. They propose a scheme, where given there is a possibility of interaction with the object, the fact of "non-interaction" can be distinguished by an experiment and hence, the presence of the object can be detected. The authors present a thought experiment: Imagine one has a bomb that is so sensitive that whenever a single photon hits it, it blows up. Would it be possible to detect the bomb using photons without destroying it? Classically it would be impossible, quantum mechanics, however, gives some chance (25% to be precise).

Let us call bomb - the "object" and photon - "probe". Authors use standard Mach-Zehnder interferometer and single-photon source. Throughout the paper we will call such a protocol EV IFM. As shown in Fig. 1, without the object blocking any of its arms, one of the interferometer output ports will always be light, and the other - dark. If we block one of the interferometer arms using our object, there is 50% chance of the photon being scattered by the object, 25% chance of arriving at what was previously called "light" port (which gives no information about the presence of the object) and 25% chance of arriving at the "dark" port. Therefore we have a 25% chance of detecting the object without interacting with it.

In case the photon is recycled after exiting through the light port (Fig. 2) the efficiency of the described device may be boosted. The maximum efficiency boils down to the ratio of the probability of exiting through the dark port if there's an object inside (25%) over the sum of

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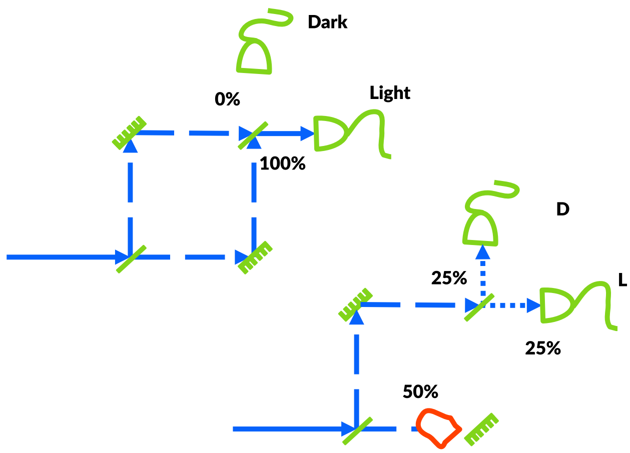

Fig. 1 Mach-Zehnder interferometer without and with an object in it. In case nothing blocks interferometer paths the photon arrives with 100% probability into the Light detector. In case there is an object blocking one of the interferometer paths there is 50% chance of scattering off the object, 25% probability of arrival into the Light detector and 25% probability of arriving at Dark detector. Therefore if we observe detection event at the Dark detector - we are able to ascertain the object's presence keeping the object and the probe intact

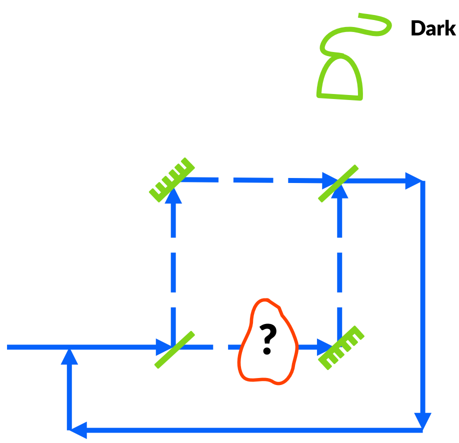

Fig. 2 EV IFM setup with photon exiting towards the Light detector being recycled. In the best-case scenario such a setup allows for 50% chance of successful object detection and 50% chance of scattering off the object

probabilities to scatter off the object (50%) and to exit through the dark port (25%). Therefore, in case the object is inside, there's 25/75 = 1/3 probability of a successful detection without interaction. If the transparency of beamsplitters is changed (almost all of the probability density goes through the non-blocked arm of the beamsplitter, and the second beamsplitter lets almost all of the probability density towards the light detector) and the photon exiting through the light port gets reused, it is possible to get at most 50% efficient detection of the photon. Meaning, given the object is inside, there would be $\frac{1}{2}$ chance of scattering event and $\frac{1}{2}$ of detecting the photon in the dark detector without interaction [3].

Note that whenever a setup recycling a photon is discussed (Figs. 2, 3 and further) it is impossible to create a static setup and the photon has to be switched out of the setup by a device that is plugged in at the right time during the experiment or by changing the configuration of the setup at the right time, for example, removing one of the mirrors that recycle the photon.

Zeilinger, Kwiat and Kasevich [4] upgrade the original EV setup to push the object detection efficiency arbitrarily close to unity. They employ Quantum Zeno effect so that the object, if placed into the device, would impede the gradual rotation of the probe photon's polarization (Fig. 3). Hence, after a sufficient amount of iterations the state of the photon would get noticeably changed only if the object wasn't inside the device. We will call such a protocol Zeno IFM.

Since then the idea of Interaction-free measurement has influenced both theoreticians and experimentalists. Conceptual advances like Hardy's Paradox [5] and inquiry into fundamental aspects of interaction-free [6–9], new proposals for quantum computation [10–14] as well as advances in measurement, imaging and detection [15–18] have sprung up.

One avenue, however, very closely related to the earliest developments of IFM, has never been explored. This avenue is extension of the IFM protocol to multiple objects. It follows logically from the essence of the IFM which does not only preserve the object of the measurement, but also the probe. And if we get to keep the probe, we might as well use it to measure the next object. In this work we explore the ways in which such an extension might be made.

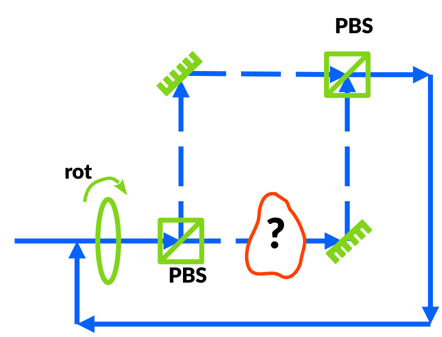

Fig. 3 Zeno IFM setup that allows for object detection efficiency arbitrarily close to unity. It employs polarizing beamsplitters and polarization rotator. In case object is inside the device it inhibits gradual rotation of photon's polarization through quantum Zeno effect. As a result after multiple cycles presence or absence of the object inside the device is reflected in photon's polarization which can later be read off

2 Multi-object interaction-free measurement

For our purposes and for clarity of exhibition the inner workings of the EV EFM or Zeno IFM may be abstracted away. The properties that are important to us are the probability of successful detection of the object inside the setup and the information flows (how the information about the objects presence is encoded). That is why we will denote the device probing object's presence as a box with one input port and two output ports (Fig. 4.)

We would like to point out that there has been considerable conceptual controversy about whether the output that we call NotA is a result of IFM. The problem being that if there is no object blocking the path of the probe we can not generally claim that the probe hasn't been in the vicinity of the potential object's location. Hence we can not generally ascertain the object's absence in the setup in an IFM way. We point the interested reader to [6] and references therein where this and other conceptual IFM controversies are discussed in detail and specifically to [10, 19] where this issue is used for deriving limitations on Interaction-Free sensing and computation.

Imagine there are two objects A and B. Each of which can have two possible configurations - "being there" or "not being there". Let's denote those by A, notA, B, notB. The whole system, therefore, consisting of two objects can now be in 4 possible configurations: A & B, A & notB, notA & B, notA & notB. Therefore, for such case one would require there to be four distinguishable experiment outcomes.

In order to be able to perform such a measurement, we should modify the initial IFM protocol in a following way. We should link multiple IFM devices so that when a single photon has gone through the compound setup, at its output there should be a possibility to read off one of the 4 configurations of the system. One of the most straightforward ways would be to use a single IFM device to determine the state of the first object and then, instead of two detectors, attach two additional IFM devices to each of the output ports (as shown in Fig. 5). Those will measure the state of the second

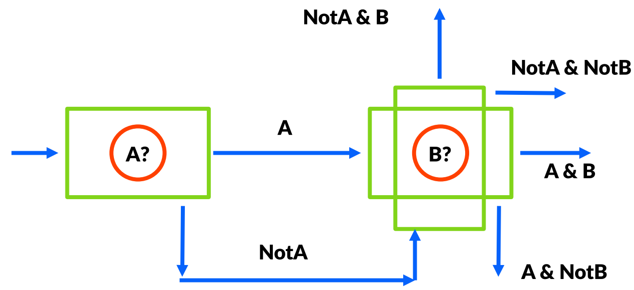

Fig. 5 IFM of two objects. Each of the output ports of the device probing the fiirst object is connected to a separate device probing the second object. In total there are 4 output ports for the 4 logical configurations of the system of 2 objects

object, conditioned on the state of the first. So that in the end by detecting a photon on one of the four output ports (2 for each secondary IFM devices), we would be able to learn the state of the whole system.

Let us consider the case when ZenoIFM is used as the building block for the compound setup. As discussed before, it allows to bring the probability of detecting the object arbitrarily close to unity [4]. Therefore the four system configurations might be distinguished. The elements of the separate building blocks - mirrors, beamsplitters, polarization rotators, may be arranged in a way that the overlapping devices don't inhibit each other (Fig. 6).

Such a setup allows for easy post-processing of the output photon because there are spatially distinct output ports. However the complexity of such a device scales exponentially - to ascertain the presence of 3 objects we need 4 more overlapping devices giving 8 output ports in total. Moreover, when we overlap the devices we are probing the object from different sides and therefore this setup implicitly assumes that the object is uniformly opaque in all directions - assumption that might not always hold. This problem might

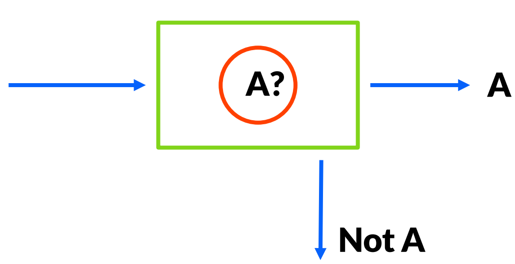

Fig. 4 Abstract IFM device. Any IFM device may be represented as a box with potential object inside, 1 input and 2 output ports

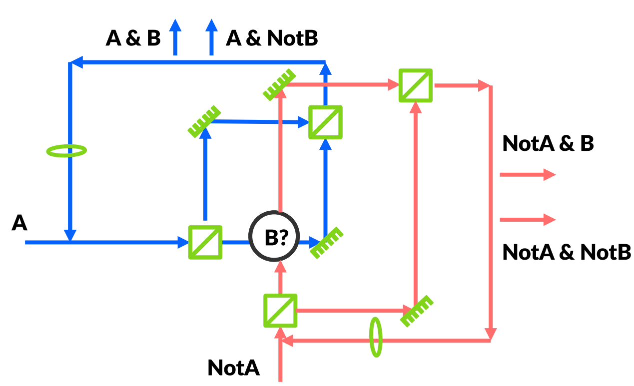

Fig. 6 Arrangement of the beamsplitters, mirrors, polarization rotators for the case of overlapping ZenoIFM devices probing the same object

tentatively be alleviated by overlapping secondary devices in a way that one's devices input port is other device's output port, but this solves the problem for two objects and not for three or more. All in all, overlap of IFM devices is good as a conceptual model, and encoding of information into spatial degrees of freedom of the photon allows for easy manipulation and post-processing of data. The drawbacks are scalability with the number of objects that are being measured.

Let us now describe a modification of the previous setup that scales better with the number of objects and does not assume the object is homogenously opaque. In this setup a temporal degrees of freedom of the photon are used (Fig. 7). Object A is potentially inside the first IFM device and object B - inside the second IFM device. No extra overlapping devices are present. Instead, both outputs of the first device corresponding to A and notA are fed into the input port of the second device. This is done in such a way that photons coming out of different ports of the first IFM device and therefore corresponding to different logical configurations of A or notA take paths of different length before arriving to the input port of the second IFM device. Any method of lengthening the optical path of the photon could be used. As a result, the information about the first object is inscribed into the temporal degrees of freedom of the photon. Now the compound device measuring presence of two objects has only two spatially distinct output ports, but adding information of photon's arrival time allows to distinguish all four configurations of the system.

Such a setup scales linearly with object number - we need as many IFM devices as we have objects and the object number is limited by photon's coherence length and time resolution of the detectors. In case of three or more objects time delays may be different for every object so that each configuration of the cumulative system corresponds to a distinct sum of time delays. Overall, inscribing information about the system into the temporal degrees of freedom of the probe is a more scalable approach. The costs being more effort in processing the results both in terms of the necessity to account for the arrival time of the photon and in terms of difficulty to use the photon in further manipulations (it is easier to arrange interference of two out of eight spatial paths of the photon's wavefunction than to arrange interference of two out of eight temporally distinct photon's wavefunction branches).

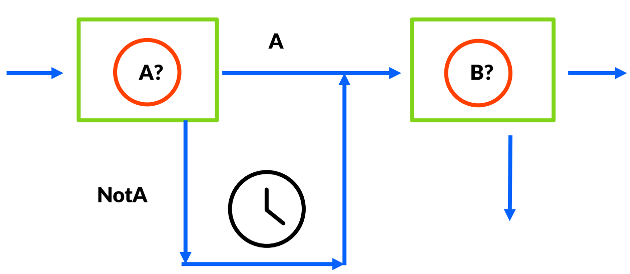

Fig. 7 IFM of two objects where the information about the first object is encoded into photon's temporal degree of freedom (arrival time). Outputs of the first measurement enter the second device through the same input port, but the branch corresponding to NotA case takes longer route and gets into the second device later

Throughout the analysis we have assumed ZenoIFM device as a building block for the compound device. Let us briefly discuss the case of a simpler EVIFM as a building block. If we take the most efficient variation of the EVIFM, the one that recycles the photon exiting from the light port (Fig. 2), efficiency of which is 50% successful detection of the object and 50% - event of scattering off the object, we arrive at efficiency of only 25% for successful detection of two objects. Such a device, when used as a building block of the compound setup does not improve any of the problems that arise when using ZenoIFM because it requires the same geometry of the compound device, but it worsens the detection efficiency dramatically.

ZenoIFM and improved-efficiency EVIFM discussed so far are interrogating the object multiple times and therefore take much longer time than basic EVIFM. Hence they might be less practical for quantum gates and other implementations where the object or its state might change rapidly.

A potentially interesting case is provided by the most simple EVIFM device that does not recycle the photon (Fig. 1). Here, in case the object is inside the device, the scattering probability is 50%, probability of successful detection is 25% and probability of obtaining no information about the object (because signal A and notA mix in the light port) is 25%. This mixing of information might be useful in creating and manipulating the entanglement in case the objects inside the devices are quantum. Indistinguishability of certain aspects of the system is an important ingredient in entanglement creation [20, 21]. Although the efficiency of chained EVIFM devices falls rapidly, in case we are interested in creation and manipulation of entanglement rather than robust measurement of the objects' properties, low efficiency is not a very large cost. Moreover, as the photon goes only once through each device we are less bound by photon's coherence length and could potentially chain more objects.

Entanglement creation and manipulation by making information about certain set of quantum objects indistinguishable could also be implemented in the setups with ZenoIFM. For example, assuming quantum objects inside chained devices with time delay geometry, we could arrange time delays in a way that some of the configurations that are distinct would correspond to the same time-delay sum and effectively become indistinguishable. As the compound system consists of separate quantum objects, the right choice of indistinguishable system configurations would result in entanglement between particular quantum objects. Entanglement generation in the spatial-encoding geometry could be obtained by interfering the photon output paths of the setup corresponding to distinct system configuration, measuring the photon and post-selecting the systems of object based on the measurement results.

Being able to interrogate two or more objects at once one obtains enough information to create two- and more bit logical gates. In our case photon outputs could be used directly as truth values on which to create logical gates without an intermediate step of comparison of outputs of object A interrogation and object B interrogation. This step is implicit in all of the aforementioned setups. Moreover following the idea in [15] where it is suggested that IFM might be used to image the retina when the light doesn't fall on it, multi-object IFM might be used to probe systems where the state of one object is very sensitively dependent on the state of the other and the system altogether is very sensitive to light. In such a case multi-object IFM allows for interaction-free-measurement of the compound system.

3 Conclusion

Multiple-object IFM is a natural extension of the idea of Interaction-free Measurement. It uses the fact that during this type of measurement both the object and the probe remain intact (keeping in mind, of course, all of the limitations of the term "Interaction-Free" that were outlined by foundational research on IFM). We have presented a conceptual framework and two possible setups that allow to interrogate multiple objects with a single probe. The first setup uses spatial degrees of freedom of the photon (paths) to encode the information about objects' presence, the other one uses temporal degrees of freedom (arrival times). Both setups have their own advantages in terms of scalability with the number of objects, difficulty of post-processing the outputs and complexity of physical implementation. The building block for both setups is the ZenoIFM device, which was chosen over EVIFM device due to its superior detection efficiency.

We have also outlined the potential applications of such a device in probing compound systems sensitive to light, creation of logical gates without intermediate steps and, in case the objects inside the device are quantum, creation and manipulation of entanglement.

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Author contributions Both authors contributed equally to the creation of the manuscript.

Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare no Conflict of interest.

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