Quantum interaction-free measurement

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ABSTRACT

"Interaction-free measurements" (IFM) originate from the latest quantum interferometric technologies. The latest research of quantum optics demonstrates, by using the complementary wavelike and particlelike natures of photons, it is possible to make interaction-free measurements by which the presence of an object can be determined with no photons being absorbed. The paper introduces the concept of "Interaction-free Measurement" (IFM), the original Elitzur-Vaidman scheme, the "High Efficiency Interaction-free Measurement", the application of quantum Zeno effect and the improved scheme proposed by Kwiat et al. The EV scheme is implemented in a Mach–Zehnder interferometer. Theoretically this paper also draws a conclusion in IFM feasibility by analyzing the wave functions of photon at various locations in the interferometer.

Key words:
Interaction-free Measurements (IFM); Quantum Zeno effect; Quantum interferometric technologies; Mach–Zehnder interferometer

1. INTRODUCTION

Nobelist Dennis Gabor, who invented holography, asserted (in 1962) in essence that no observation can be made with less than one photon striking the observed object. In the past several years, however, physicists in the increasingly bizarre field of quantum optics have learned that this claim is incorrect[1].

The latest research of quantum optics demonstrates, by using the complementary wavelike and particlelike natures of photons, it is possible to make interaction-free measurements (IFM) in which the presence of an object can be determined with no photons or any other objects being absorbed.

The idea was first proposed by Elitzur and Vaidman. In the Elitzur-Vaidman (EV) interaction-free measurement (IFM) scheme, the measurement is interaction-free at most half of the time, or at probability of 50%.[2,3]
Later, Kwiat et al.[4] attempted to improve the IFM efficiency by using the quantum Zeno effect, and demonstrated that the probability of performing IFM could reach up to 85% in the improved apparatus.

2. BASIC PRINCIPLE AND EXPERIMENT SETUP OF IFM

2.1. Basic principle of EV scheme

Interaction-free measurements (IFM) originate from the latest quantum interferometric technologies. The EV scheme[2] is implemented in a Mach–Zehnder interferometer (shown in Fig. 1).The interferometer consists of two beam splitters (B_1 and B_2) and two reflectors (M). The upper and lower optical paths are adjusted to be the same length, and at the same time the reflectivity of the first beam splitter (R_1) keeps the same as the transmissivity of the second one (T_2). Due to the "constructive interference" of optical field[2,5], when there is no object in two arms of the interferometer, photons entering the interferometer always reach detector D_1 (corresponding to constructive interference) and never detector D_2 (corresponding to destructive interference).

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When there is any object in one of the arms of the interferometer (Fig. 2), the constructive interference will be destroyed. The photons, with particle-like behavior, enter the interferometer and lead to three possible cases: 1) absorbed by the object; 2) reflected to the detector D_1 by the beam splitter B_2, as if there were no object in the optical path; 3) pass through the splitter B_2 and reach the detector D_2. The last case is called "interaction-free measurement". The information about the presence of an object in the optical path is obtained without photons being absorbed.

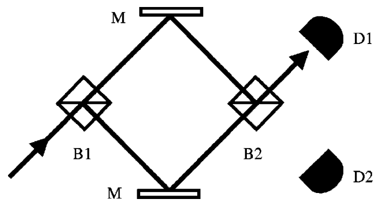


Fig. 1. No object placed in both arms of the interferometer

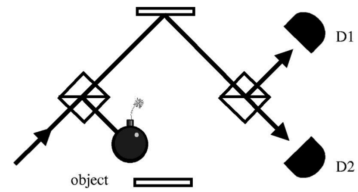


Fig. 2. Object placed in one arm of the interferometer

2.2. Theory

Fig. 3 illustrates the wave functions of photons in various positions without object in the interferometer. After passing the second beam splitter, the outgoing wave functions created by the double-arms-interference are respectively given as follows[6]

$$\left|d\right\rangle = \sqrt{R_2}\left|b\right\rangle + i\sqrt{T_2}\left|c\right\rangle = i\left(\sqrt{T_1R_2} + \sqrt{R_1T_2}\right)\left|a\right\rangle \tag{1}$$

and

$$\left|e\right\rangle = i\sqrt{T_2}\left|b\right\rangle + \sqrt{R_2}\left|c\right\rangle = \left(-\sqrt{T_1T_2} + \sqrt{R_1R_2}\right)\left|a\right\rangle \tag{2}$$

where $\sqrt{T_1}$, $\sqrt{R_1}$, $\sqrt{T_2}$ and $\sqrt{R_2}$ are the amplitudes of wave functions when passing through the beam splitters B_1 and B_2 respectively.

Because $T_2 = R_1$ (it must also be true that $R_2 = T_1$), and $R + T = 1$ holds true for each beam splitter, the following equation will yield

$$-\sqrt{T_1T_2} + \sqrt{R_1R_2} = -\sqrt{T_1R_1} + \sqrt{R_1T_1} = 0 \tag{3}$$

That is the wave function $\left|e\right\rangle = 0$, which means that the photons are impossible to reach the detector D_2 (See Fig. 1).

When an object is placed in one of the two arms of the interferometer (See Fig. 2), only the reflection and transmission probability of photons passing through every beam splitter is necessary to be considered because there is no interference action. If a photon is reflected by the first beam splitter, it means that it will be absorbed, and the probability of this absorption is $P_{abs} = R_1$. If a photon is transmitted by both of the beam splitters (Case 3), it is deemed that an "interaction-free measurement" is carried out successfully, and the probability is $P_{IFM} = T_1 T_2$.

The efficiency of ''Interaction-free Measurement"[6] is defined as $\eta = \frac{P_{IFM}}{P_{abs} + P_{IFM}}$, so the efficiency of IFM can be simplified as

$$\eta = \frac{P_{IFM}}{P_{abs} + P_{IFM}} = \frac{T_1T_2}{R_1 + T_1T_2} \tag{4}$$

Due to $T_2 = R_1$ and $R_1 + T_1 = 1$, the efficiency can also be simplified as

$$\eta = \frac{T_1}{1+T_1} = \frac{(1-R_1)}{1+(1-R_1)} = \frac{1-R_1}{2-R_1} \tag{5}$$

It can be concluded from Equation (5) that "interaction-free measurement" can be implemented with maximum efficiency of 50% by reducing the reflectivity of the corresponding beam splitter.

Fig. 4 illustrates[6] the relation between the reflectivity R_1 and the efficiency of IFM, where the curve stands for the theoretical value of EV scheme proposed by Elitzur and Vaidman and the dots stand for the actual measured values.

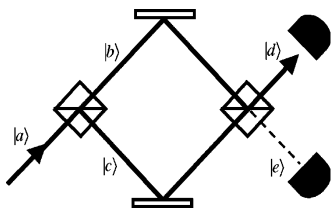


Fig. 3. Labels used for the wave functions.

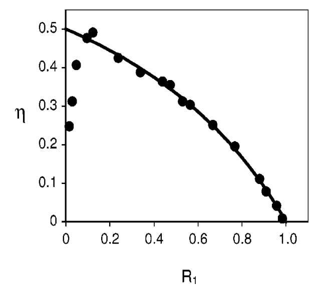


Fig. 4. Relation between reflectivity R_1 and efficiency of IFM

3. INTERACTION-FREE IMAGING EXPERIMENT

Based on the EV scheme, Andrew G. White[7] and Jay R. Mitchell from Los Alamos National Laboratory designed an imaging system of IFM, and obtained high-resolution (10μm) scanning image for one-dimensional profiles of a variety of objects such as human hair, optical fibers and metal wires as well as cloth filament.

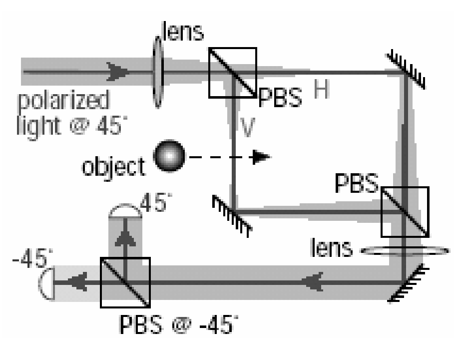


Fig. 5. IFM imaging system of Los Alamos National Laboratory

The IFM implementation is similar to the EV scheme, and the imaging system applied is a Mach–Zehnder interferometer equipped with polarizing beam splitters whose reflectivities are adjustable. The mechanism adopts an automatic decoding platform and a high-resolution encoder to scan stepwise the objects. White's group took two different scans: the first was an interaction-free measurement and the second was a normalized transmission scan.

Table 1 shows the measured values obtained by Andrew G. White, Jay R. Mitchell and et al. for different methods such as "interaction-free measurement", transmission scan, microscope and diffraction.

From the above scanning results of one-dimensional objects, it is obvious that the uncertainties of the widths of IFM and transmission scan are approximately ±1%, except ±2% for cloth filament. The result from IFM scan basically corresponds with those from other measuring methods. By contrast the validity of IFM imaging can be demonstrated.

Tab. 1. Results of different methods for measuring one-dimensional objects

Method / Width (μm) / object	IFM scan	transmission scan	microscope	diffraction
Thin metal wire	95.3	96.6	95.5±1.6	97.0±0.5
Thick metal wire	160.2	162.7	159.1±1.6	159.5±2.0
Cloth filament	16.6	16.3	12.6±0.6	15.4±1.2
Human hair filament	22.8	24.7	25.1±0.9	26.2±0.6
Thin optical fiber	125.7	123.9	123.5±1.9	123.2±3.6
Thick optical fiber	208.0	207.5	207.9±3.0	208.3±2.5
Slit	12.5	13.1	N.A.	19.2±1.2

4. DISCUSSION OF HIGH-EFFICIENT IFM

Many physicists attempt to search for IFM scheme with efficiency higher than 1/2, and the quantum Zeno technology has shown the possibility of detecting polarized objects with probability greater than 50%.The quantum Zeno effect is first discussed in detail in 1977 by Misra, now at the University of Brussels, and Sudarshan of the University of Texas at Austin. The effect involves that repeated quantum measurements can inhibit the evolution of a quantum system and a quantum system can be trapped in its initial state. In 1980, Peres of the Technion-Israel Institute of Technology demonstrated the Zeno effect by using the polarization effect. In 1994, Kwiat of Los Alamos National Laboratory and Kasevich of Stanford University applied this technology in the high-efficiency IFM[4].

4.1. Quantum Zeno effect

Considering a system consisting of N polarizers[4], each of these polarizers rotates the polarization of incident light by an angle 90°/N. Therefore, after passing through all N of them, an initially horizontally-polarized photon will be vertically polarized. Finally, blocked by a horizontally-polarized analyzer, it will have no chance of passing through the system and getting to the detector D.

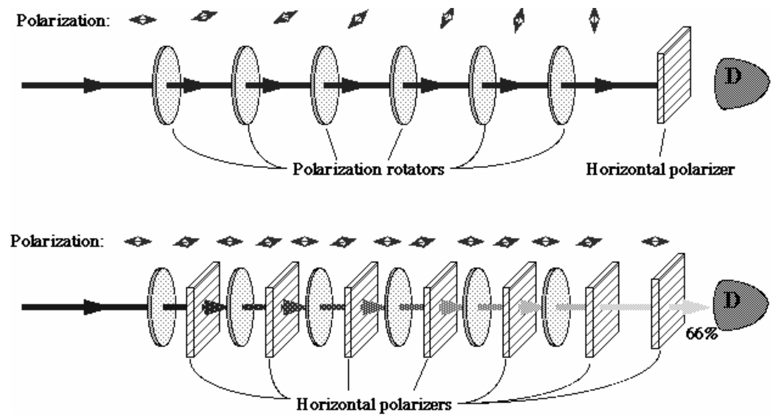


Fig. 6. Zeno effect of 6 rotators and analyzers

However, if a horizontal analyzer is inserted into the optical path behind each of "polarization unit", the polarization state of incident light will be "inhibited" in the horizontal direction. Since the probability of being transmitted through each polarization analyzer is just $\cos^2(\Delta\theta)$, the probability of being transmitted through the whole system is a function of $\left[\cos^2(\pi/2N)\right]^N \approx 1-\frac{\pi^2}{4N}$, and the complementary probability of the absorption is $\frac{\pi^2}{4N}$. Hence, by increasing the number of units and decreasing the polarization-rotation angle at each unit accordingly, the probability that the photon is absorbed by one of the analyzers can be arbitrarily low in principle[8]**.**

If the photon exits from the system still in its initial horizontal polarization state, it can be judged that polarization analyzers are present in the system. Instead of using multi rotators and analyzers, one rotator and one analyzer are used in practice. As illustrated in Fig. 7, three mirrors are arranged as spiral staircase so that the photons are reflected to attain the same effect according to the desired times.

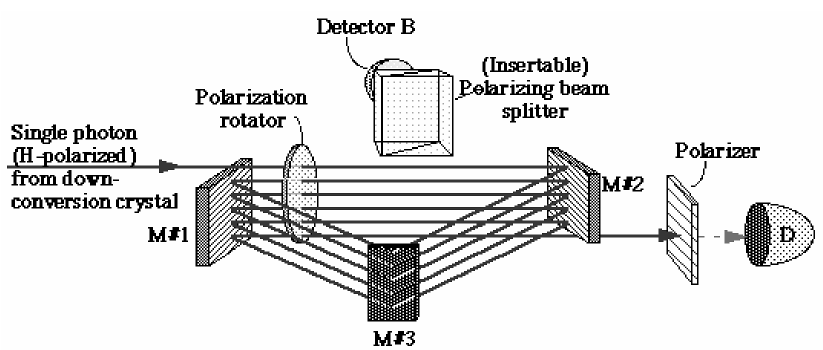


Fig. 7. Zeno effect of a spiral-staircase path

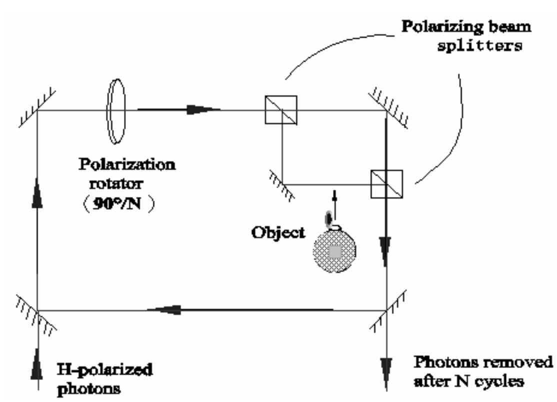
4.2. Combination of quantum Zeno technique and EV scheme

The limitation of maximum efficiency 50% can be broken through by applying Zeno technology in EV scheme, and achieve high efficiency of IMF to detect the existence of an opaque object with arbitrarily small probability of absorbing a photon[8].

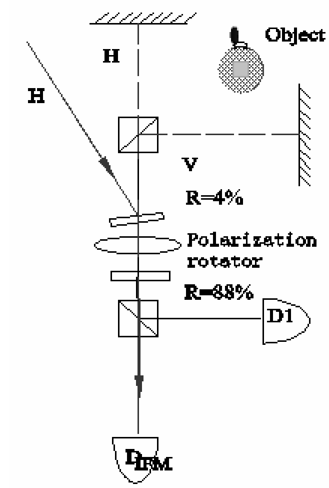
The concept of high-efficiency IFM scheme is illustrated in Fig. 8. (a). It consists of a device which verifies the quantum Zeno effect and a Mach–Zehnder interferometer equipped with polarizing beam splitters. The function of the polarizing beam splitters is to transmit the horizontally polarized light and reflect the vertically polarized one. In practice, Michelson system is adopted for simplicity. Working processes for the two systems are same in principle.

If two arms of the interferometer are not blocked, a horizontally-polarized photon will circulate in the device after entering the system. The polarizing beam splitters of interferometer do not affect the polarization state of photon, but simply break up the beam and then add it up. The polarization angle will gather after certain circulations, and eventually the initially horizontally-polarized photon will gradually turn to be vertically polarized.

But when an opaque object is placed in the vertical polarization path of interferometer, the polarization -rotating will be inhibited. The probability a photon entering the vertical-polarization path and being absorbed is low because the polarization angle is very small at each cycle. If absorption does not happen, the photon will return to horizontal polarization. If it has successfully survived every cycle, then the photon is definitely horizontally polarized.



(a)



(b)

Fig. 8. (a) Concept of high-efficiency IFM and (b) experiment setup

Finally, the photon is switched out of the system for polarization analyzing by means of high-voltage Pockel's cells[4] (Not illustrated in Fig. 8. (b)) of the interferometer arms after the desired number of cycles. The photon is then analyzed using an adjustable polarizer, and detected by a single-photon detector. In the absence of any object in the vertical-polarization arm of interferometer, the polarization will be essentially vertical, so the existence of an object in the lower path can be determined by analyzing the final photon's polarization.

As the number of circulation is increased, the polarization-rotation angle at each stage is decreased accordingly[3], so the probability of the photon transmitting will increase and thus the probability of IFM implementation will also improve (Fig. 9).

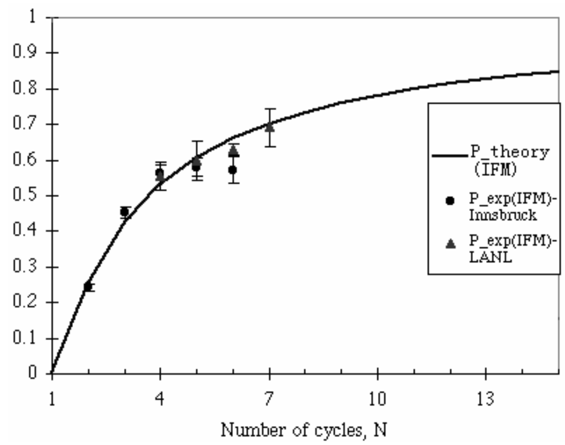


Fig. 9. Probability of the high efficient IFM implementation is up to 70% (data from Innsbruck and Los Alamos National Laboratory).

5. PROSPECT

A potential application of interaction-free measurement is the imaging of light-sensitive objects, For example, it is used to photograph living cells since it can reduce the radiation damage. The more immediate application is the imaging of Bose-Einstein condensations (BEC).[9] Because BEC is a kind of unstable Macroscopic Quantum State, IFM can get an image of the condensate without destroying the state. Interaction-free procedures could also be used to extend the creation of "Schrödinger's cat"[3] that can make a set of photons, such as 20 photons, in the same superposition. This characteristic can be applied to fabrication of quantum logic gate, which is the key device for the quantum computer. In recent years, the research of quantum device as well as optics has made great progress based on quantum mechanics effect (such as quantum coherence, quantum Tunnel, Coulomb blockade effect and so on). The researchers of Lawrence Berkeley National Laboratory and Los Alamos National Laboratory have confirmed that it is feasible, at least in theory, to realize quantum computation only by using simple component of linear optics.

The research of IFM technology, which deals with the exploration of the essence of measurement and provides new methods for quantum computation[10], will deepen our knowledge to the world and raise a new upsurge in the development and application of quantum theory in near future.

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