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Realistic Interaction-Free Detection of Objects in a Resonator

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We propose a realistic device for detecting objects almost without transferring a single quantum of energy to them. The device can work with an efficiency close to 100% and relies on two detectors counting both presence and absence of the objects. Its possible usage in performing fundamental experiments as well as possible applications are discussed.

1. INTRODUCTION

Quantum interference of individual systems has recently been found capable of detecting objects without transferring energy to them. The effect has been named *interaction-free-detection*[3] and was based on the void detections which destroy path indistinguishability. In 1986 Pavičić[(2)] formulated this in the following way. "Consider a photon experiment shown in Fig. 1 which results in an interference in the region D provided we do not know whether it arrived at the region by path s_1 or by path s_2. As is

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[3] Niels Bohr would most likely argue against the name in the following way: "It is true that in the measurements under consideration any direct mechanical interaction of the system and the measuring agencies is excluded, but... the procedure of measurements has an essential influence on the conditions on which the very definition of the physical quantities in question rests.... These conditions must be considered as an inherent element of any phenomenon to which the term "[interaction]" can be unambiguously applied."[(1)] However, the name has been rather unanimously accepted in the quantum parlance and it is likely to stay there.

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well known, the experimental facts are: If we, after a photon passed the beam splitter *B* and before it could reach the point *C*, suddenly introduce a detector in the path s_2 in the point *C* and do *not* detect *anything*, then it follows that the photon must have taken the path s_1—and, really, one can detect it in the region *D* but it does *not* produce interference there. Quantum mechanically, if we registered the interference in the region *D*, we could not find an experimental procedure to directly either prove or disprove that the photon uses both paths simultaneously. However, the fact that by detecting *nothing* in point *C* we destroy the interference implies that the photon *somehow* knows of the other path when it takes the first one." (Ref. 2, pp. 31, 32)

The photon's "knowledge" about the other path can be employed to detect an object (at point *C*) without transferring even a single quantum of energy to it. The efficiency of such an application with a symmetrical Mach–Zehnder interferometer (shown in Fig. 1) is ideally only 25% for single detections and 33% in the long run as shown in Elitzur and Vaidman's detailed formulation of the void detections in interference experiments in 1993.(3) They also showed that one could increase the ideal efficiency to 50% if an asymmetrical beam splitter were used. In 1995 Kwiat *et al.*(4) carried out Elitzur and Vaidman's proposal with an asymmetrical beam splitter using photons obtained in a parametric down conversion. In this way an efficiency close to 50% has been achieved for correlated photons. However, the realization was concerned only with the confirmation of the effect and the 50% efficiency referred to the detected photons which supported the confirmation. For, in the experiment it was necessary to select, with irises, a very small fraction of the photons originally produced in downconversion, which resulted in a net detection efficiency of only 2%. The latter efficiency can be significantly improved(5)

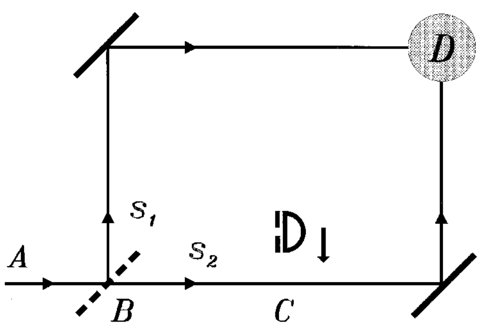

Fig. 1. Figure taken from Pavičić (1986). "By detecting *nothing* in the point *C* we destroy the interference [in the region *D*]." (Ref. 2, p. 31).

but the downconversion can hardly be used for a straightforward realistic interaction-free device.

A proposal put forward by Kwiat *et al.*[4, 6] in 1995 which aims at realistic efficiencies of *not hitting* tested objects is shown in Fig. 2. The device consists of two coupled resonators (cavities) separated by a highly reflective beam splitter and assumes inserting single photons into one of them. If an object were in the other cavity the probability of it being hit would remain comparatively low. In the absence of an object the photon should, after a certain number of cycles N, be in the right cavity with certainty. Inserting of a detector in the left cavity should verify the cases. Such an experiment would be very hard to carry out in realistic conditions even if the problem of inserting single photons and the detector were solved, in particular because no firing of the detector should mean the absence of the object and because of the high losses at the mirrors.

In 1996 Kwiat *et al.*[7] put forward another proposal, shown in Fig. 3, which is based on a previous elaboration of the optical Zeno effect. A horizontally polarized photon enters the resonator through the switchable mirror SM which keeps it in for N cycles. After each cycle the polarization rotator PR turns the initial photon polarization by an angle α. When there is no object in the resonator the wave function recombines at the polarizing beam splitter PBS within each cycle so that after $N = \pi/(2\alpha)$ cycles it exits the resonator vertically polarized. When there is an object in the resonator within each cycle we have the Malus probability $p = \cos^2 \alpha$ of the photon passing straight through the horizontally polarizing beam splitter. After N cycles the photon—horizontally polarized—exits through SM with the probability $P = p^N$. The probability of the object being hit by the photon is therefore $Q = 1 - P$. For $\alpha = 1°$, $Q = 3\%$. In this proposal, as opposed to the previous one, we do have different detectable outcomes for the presence and absence of objects. Nevertheless, one has to start again from photon pairs generated in a parametric downconversion in order to be able to determine the photon's entrance time and thus fix the number of cycles, i.e., the moment in which one should let the photon out of the resonator

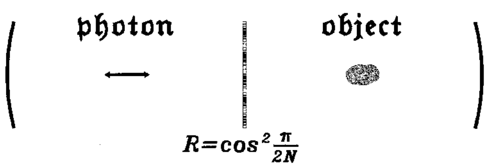

Fig. 2. Figure according to Ref. 4. A single photon inserted into the left cavity stays there when there is an object in the right cavity and moves to the right cavity when there is no object there.

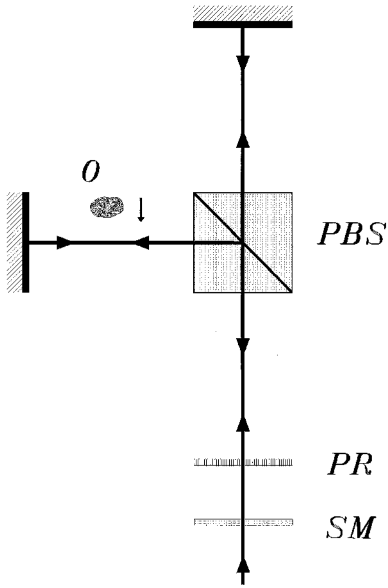

Fig. 3. Figure according to Ref. 7. A single horizontally polarized photon enters the resonator through the switchable mirror *SM* and passes the polarization rotator *PR* (which turns the polarization plane by the angle 90°/*N*) and the polarizing beam splitter *PBS N* times before exiting through *SM* horizontally polarized when there is an object in the path and vertically polarized when there is no object in the path.

through the switchable mirror *SM*. Moreover, the mirror losses will have a detrimental effect on the experiment. Actually, this effect grows with the number of cycles: the larger the latter is, the lower is the ideal theoretical value of Q, and the bigger are the losses.

In 1997 we conceived a different approach using a single monolithic total-internal-reflection resonator (MOTIRR) coupled by two frustrated-total-internal-reflection (FTIR) prisms.[8] The physical principle of the device was essentially the same as for the scheme in Fig. 4 we are going to present in this paper with the only difference that the central loops were confined within a monolithic crystal. The presence of the object causes firing of detector D_r and the absence causes firing of D_t. The losses in a MOTIRR are extremely low and go down to 0.3%.[9] Thus a realistic application of interaction-free measurements to suitable small objects has been enabled. In this paper we are proposing a general purpose interaction-

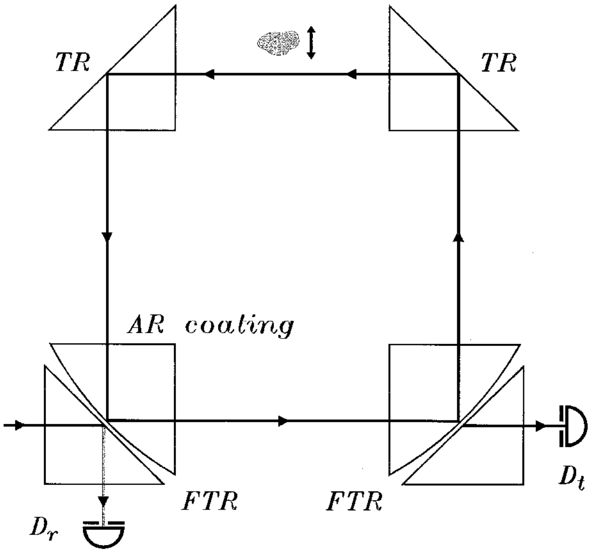

Fig. 4. Schematic of the proposed realistic interaction-free device. A single p-polarized photon tunnels (frustrated total reflection *FTR*) into the resonator. With a realistic efficiency exceeding 98% the beam makes several hundred loops guided by two total reflections *TR* and two *FTR*'s to exit into D_t when there is no object in the path. When there is an object in the resonator, the beam is reflected into D_r.

free device for all possible applications foreseen so far, calculate the losses that can be expected in realistic conditions, and show that the present setup evades limitations of the previous proposals. The elaboration differs from our former elaborations(8, 21) in making use of data from both D_r and D_t detectors thus greatly reducing the phase mismatch effect. Such combined statistics also enable one to gain information on gray objects.

Suggested applications of the interaction-free measurements are numerous and range from the foundational physical experiments and experiments in medicine. Let us just cite some of them. It has been used to show that under a plausible condition Lorentz-invariant realistic interpretations of quantum mechanics are not possible.(10) A preparation of a very well-localized atom beam by means of a Mach–Zehnder interferometer for neutrons without physical interaction has been proposed(11) and the first interaction-free experiment with neutrons has already been carried out.(12) A possible interaction-free experiment in quantum dot systems has been discussed.(13) An optical device for erasing fringes of atom interference without disturbing either the spatial wave function or its phase has been proposed,(14) thus strengthening the result of Scully *et al.*(15) See also Ref. 16 which is a further elaboration and discussion of the proposal. Testing of Bose–Einstein condensates (which can be blown apart by even a single photon) has been seen recently as the most immediate possible application, [7] and also the preparation of a superposition at a macroscopic scale,[7] and, in the end, several more distant possible applications such as selecting particular bacteria without killing them, safe X-ray photography, quantum computer application, etc.[17] In any case we share the feeling that "the situation resembles that of the early years of the laser when scientists knew it would be an ideal solution to many unknown problems."[7]

2. EXPERIMENT

Figure 4 shows an outline of the proposed experiment. When there is no object in the device, an incoming laser beam is almost totally transmitted (up to 98%) into detector D_t, and when there is an object, an incoming laser beam is being (ideally) totally reflected into detector D_r. The device consists of four prisms forming a resonator. The prisms are designed so that their entrance and exit faces are at right angles to the beam making rectangular loops and are covered with multilayer antireflection coating to minimize reflection losses. The entrance prism is coupled to the adjacent loop prism by the frustrated total reflection, which is an optical version of quantum mechanical tunneling.[9] Depending on the dimension of the gap between the prisms, one can well define reflectivity R within the range from 10^{-5} to 0.99995. The uniqueness of the reflectivity at the gaps and at the same time no reflectivity at the entrance and exit faces of the prisms for each photon is assured by choosing the orientation of the polarization of the incoming laser beam perpendicular to the plane of incidence. As a source of the incoming beam a continuous wave laser (e.g., Nd:YAG) should be used because of its coherence length (up to 300 km) and its very narrow linewidth (down to 10 kHz in the visible range).[18]

Let us now determine the intensity of the beam arriving at detector D_r when there is no object in the path. A description of the device is formally equivalent to a Fabry–Perot-type of resonator with standard mirrors up to the phase shifts at the FTR's which we take into account so as to include it into the phase which is being added by each round trip. (Details of the calculations are given in Ref. 19.) The portion of the incoming beam of amplitude $A(\omega)$ reflected at the FTR inner face of the incoming prism is described by the amplitude $B_0(\omega) = -A(\omega)\sqrt{R_1}$, where R is reflectivity. The remaining part of the beam tunnels into the resonator and travels around the resonator guided by one frustrated total reflection (with reflectivity $\sqrt{R_2}$ at the face next to the right prism where a part of the beam tunnels out into D_t) and by two proper total reflections. The losses for such a set-up—as opposed to standard mirror Fabry–Perot resonators—are very low as calculations and recent experiments show: below 2%[20] for the type presented here and even below 0.3%[9] for the set-up with a monolithic resonator we presented in Ref. 8. The losses in the present set-up are mostly due to absorption and scatter in the multilayer antireflection coatings and the crystals and to a much smaller extent due to imperfect total reflections. After a full round trip the following portion of the beam joins the directly reflected portion of the beam by tunneling into the left prism: $B_1(\omega) = A(\omega)\sqrt{1-R_1}\sqrt{R_2}\sqrt{R_3}\sqrt{R_4}\sqrt{1-R_1}\,e^{i\Psi}$, where $\psi = (\omega - \omega_{res})T$ is the phase added by each round trip which also includes phase shifts at the gaps; here ω is the frequency of the incoming beam, T is the round-trip time, ω_{res} is the resonator frequency, and $\sqrt{R_3}$, $\sqrt{R_4}$ are the two (realistic, and therefore not equal 1) total reflectivities in which we also include the aforementioned absorption and scatter (which can be treated as transmitivities); here we introduce $\rho = \sqrt{R_3 R_4}$ as a measure of all the losses; $\rho = 1$ corresponds to an ideal case with no losses.

Each subsequent round trip contributes to the geometric progression

$$B(\omega) = A(\omega)\{-\sqrt{R_1} + (1-R_1)\,\rho\sqrt{R_2}\,e^{i\Psi}[1 + \rho\sqrt{R_1 R_2}\,e^{i\Psi} + \cdots]\}$$

$$= A(\omega)\left\{-\sqrt{R_1} + \frac{(1-R_1)\,\rho\sqrt{R_2}\,e^{i\Psi}}{1-\rho\sqrt{R_1 R_2}\,e^{i\Psi}}\right\} \tag{1}$$

so as to yield the following probability of the beam being reflected into D_r

$$B(\omega)\,B(\omega)^* = A(\omega)\,A(\omega)^*\left[1 - \frac{(1-R_1)(1-\rho^2 R_2)}{1-2\rho\sqrt{R_1 R_2}\cos\psi + \rho^2 R_1 R_2}\right] \tag{2}$$

In an analogous way we obtain the probability of the beam being transmitted into D_t

$$C(\omega)\,C(\omega)^* = A(\omega)\,A(\omega)^*\,\frac{(1-R_1)(1-R_2)}{1-2\rho\sqrt{R_1 R_2}\cos\psi + \rho^2 R_1 R_2} \tag{3}$$

Since the frequency of the input laser beam can never precisely match the resonance frequency we make use of a Gaussian wave packet $A(\omega) = A\exp[-\mathcal{T}^2(\omega-\omega_{res})^2/2]$, where $\mathcal{T}$ is the coherence time which obviously must be significantly longer than the round-trip time T. Thus we describe the incident wave by

$$E_i^{(+)}(z,t) = \int_0^\infty A(\omega)\,e^{i(kz-\omega t)}\,d\omega \tag{4}$$

the reflected wave by

$$E_r^{(+)}(z', t) = \int_0^\infty B(\omega)\, e^{i(kz' - \omega t)}\, d\omega \tag{5}$$

and the transmitted wave by

$$E_t^{(+)}(z', t) = \int_0^\infty C(\omega)\, e^{i(kz' - \omega t)}\, d\omega \tag{6}$$

The energy of the incoming beam is the energy flow integrated over time:

$$I_i = \int_{-\infty}^\infty E_i^{(+)}(z, t)\, E_i^{(-)}(z, t)\, dt = \int_0^\infty A(\omega)\, A^*(\omega)\, d\omega \tag{7}$$

The energies of the reflected and transmitted beams are given analogously by $I_r = \int_0^\infty B(\omega)\, B^*(\omega)\, d\omega$ and $I_t = \int_0^\infty C(\omega)\, C^*(\omega)\, d\omega$, respectively.

The efficiency of the suppression of the reflection into D_r is given by

$$\eta = 1 - \frac{I_r}{I_i} = (1 - R_1)(1 - \rho^2 R_2)\, \Phi \tag{8}$$

and the efficiency of the throughput into D_t by

$$\tau = \frac{I_t}{I_i} = (1 - R_1)(1 - R_2)\, \Phi \tag{9}$$

where

$$\Phi = \frac{\displaystyle\int_0^\infty \frac{\exp[-\mathcal{T}^2(\omega - \omega_{res})^2/2]\, d\omega}{1 - 2\rho\sqrt{R_1 R_2}\cos[(\omega - \omega_{res})\,\mathcal{T}/a] + \rho^2 R_1 R_2}}{\displaystyle\int_0^\infty \exp[-\mathcal{T}^2(\omega - \omega_{res})^2]\, d\omega} \tag{10}$$

where $a \equiv \mathcal{T}/T$ is the ratio of the coherence time $\mathcal{T}$ and the round-trip time T. The coherence length should always be long enough ($a > 200$) to allow sufficiently many round trips (at least 200). Φ turns out to be very susceptible to the small changes of ρ so as to yield rather different outputs of τ in opposition to η (cf. Figs. 5 and 6).

Obviously both η and τ should be as close to 1 as possible. A computer optimization shows that this can best be achieved by taking $R_1 = R_2$. In Figs. 5 and 6 we give the values of η and τ, respectively, for ρ's which

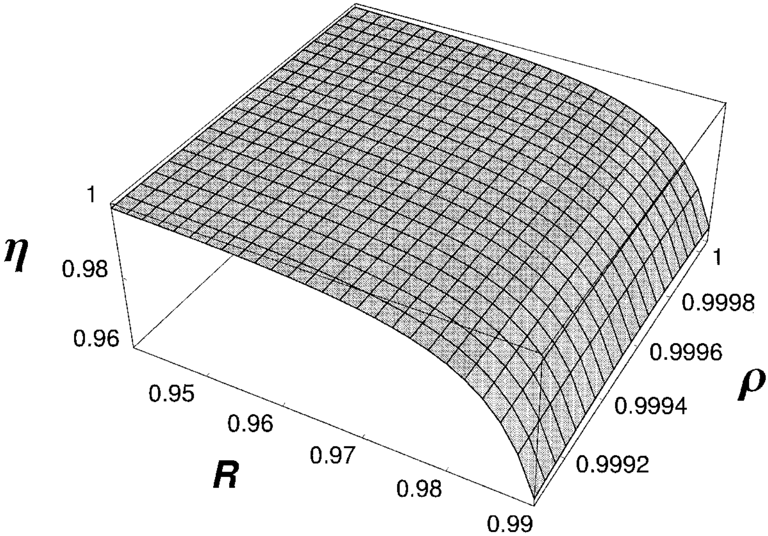

Fig. 5. The efficiency of the suppression of the reflection into D_r when there is no object in the resonator as given by Eq. (8). R is the frustrated total reflection at the two coupling output prisms and ρ is the measure of losses as defined for Eq. (1).

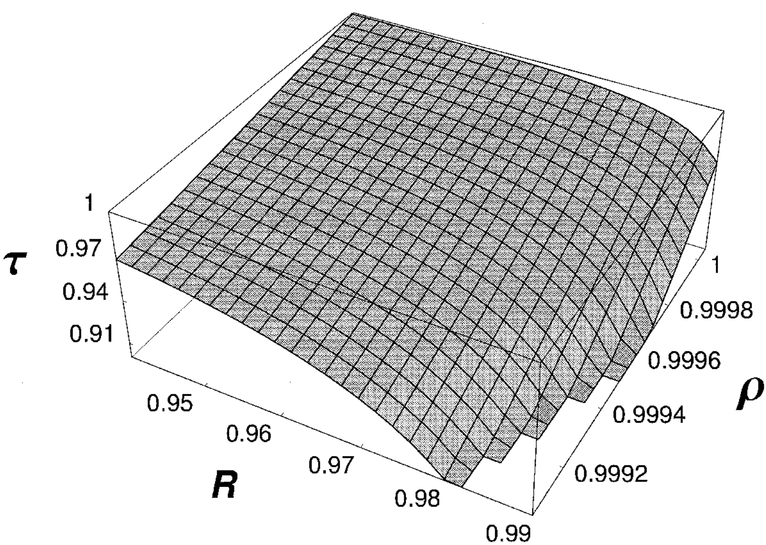

Fig. 6. The efficiency of the throughput into D_t when there is no object in the resonator as given by Eq. (9). R and ρ are defined as in Fig. 5.

correspond to the throughput τ of about 98% which is considered achievable. The total reflectivities with losses below 10^{-6} are achievable so that the given values for ρ are not the problem so far as the total reflection is considered. As for the throughput τ the given values for ρ are also apparently achievable. If, however, the absorption of antireflection coating turns out to be too high, one can always substitute Pellin–Broca prisms with entrance and exit faces at Brewster's angles (i.e., no reflection losses) for the present prisms with the multilayer antireflection coatings.(19)

In order to carry out the experiment we have to lower the intensity of the beam until it is likely that only one photon would appear within an appropriate time window (1 ms − 1 μs < coherence time), which allows the intensity in the cavity to build up. The values for $1-\eta$ are probabilities of detector D_r reacting when there is no object in the system. The values for τ are probabilities of detector D_t reacting when there is no object in the system. For example, for $R = 0.98$ and $\rho = 0.9999$ one obtains $\eta = 0.99$ and $\tau = 0.98$. η and τ in Figs. 5 and 6 are calculated for $a = 500$, i.e., for 500 round trips which are multiply assured by continuous-wave laser coherence length. Since we did take possible background counts into account by using the Gaussians for the calculation, we can equally rely on D_r and on D_t firing; also, we can use this fact for tuning the device. A response from D_r means that there is an object in the system. In the latter case the probability of the D_r response is ideally R, the probability of a photon hitting the object is $R(1-R)$, and the probability of photon exiting into D_t detector is $(1-R)^2$. It should be noted that under realistic conditions there will be a certain amount of phase mismatch in the process of injecting the light into the resonator. This will result in an increase of the reflected light dependent on the actual beam parameters, in the absence of the object. Hence the rate of "false signals" from detector D_r indicating the presence of an object when there is actually none there, will grow slightly. However, this undesired effect could be greatly reduced by looking at the responses from detector D_t. A "false signal" will be followed by a D_t signal with a probability of about 98%, while a "good signal" will be followed by a D_t signal with a probability of about 2% for $R = 0.98$.

We start each testing by opening a gate for the incident beam and after either D_r or D_t fires, the testing is over. The cases when detectors fail to react either because of their inefficiency are not problematic because single photon detectors with 85% efficiency are already available. Such a failure would result in a slightly bigger time window, so that the chance of a photon hitting an object would remain practically unchanged. Thus, a possible 300 km coherence length of cw lasers does not leave any doubt that a real experiment of detecting objects (with an efficiency of over 98%) without transferring a single quantum of energy to them (with the same efficiency) can be carried out successfully.

3. CONCLUSION

We have shown that with our resonator based on total reflections and frustrated total reflections, interaction-free measurements can be carried out with a realistically achievable efficiency of 98%. The proposed design makes the device not only very suitable for the foundational experiments reviewed in Sec. 1 but also a good candidate for a more general application, e.g., in medicine, for X-raying patients practically without exposing them to radiation. The latter application was not possible with previous set-ups because they were all based on mirrors and the losses at X-ray mirrors could be too high for building a realistic interaction-free device. The total reflections we use are, however, applicable to X-rays and often used for constructing X-ray lasers. On the other hand, our setup with two outputs is easily applicable to interaction-free detection of *gray* objects where one concludes on the level of *grayness* by means of the statistics of repeated testings.

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