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Resonance energy-exchange-free detection and "welcher Weg" experiment

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Abstract

It is shown that a monolithic total-internal-reflection resonator can be used for energy-exchange-free detections of objects without recoils. Related energy-exchange-free detection of *"welcher Weg"* is discussed and an experiment with an atom interferometer is proposed. The obtained results are in agreement with quantum theory.

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1. Introduction

Recently the old quantum *welcher Weg* (*which path*) reasoning has been used to devise experiments in which there is a certain probability of detecting an object without transferring a single quantum of energy to it [1-6]. The experiments are usually called *interaction-free* experiments but we use the name *energy-exchange-free* experiments in order to stress the fact that the detected object do interact with the measuring apparatus even when no quantum of energy $h\nu$ is transferred to it[3]. In effect, the reasoning, in an ideal case, is the following one. After the second beam splitter of a Mach-Zehnder interferometer one can always put a detector in such a position that it will never (i.e., with probability zero) detect a photon. If it does, then we are certain that an object blocked the *"other"* path of the interferometer. The Mach-Zehnder interferometer itself cannot be used for practical energy-exchange-free measurement because of its very low efficiency (under 30%). Therefore Paul and Pavičić [6] recently proposed a very simple and easily feasible energy-exchange-free experiment based on the resonance in a single cavity whose efficiency can realistically reach 95%. As a resonator the proposal used a coated crystal which, however, reduced its efficiency.

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[3] A slight twist (in brackets) of Niels Bohr's words might illuminate our decision: "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... [T]hese conditions must be considered as an inherent element of any phenomenon to which the term "[interaction]" can be unambiguously applied." [7].

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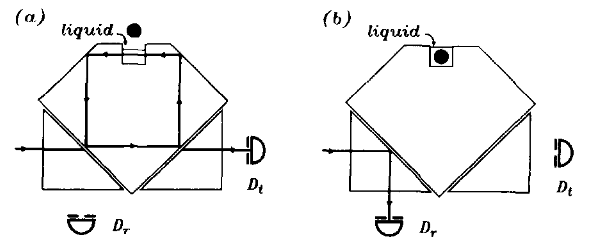

Fig. 1. Lay-out of the proposed energy-exchange-free experiment; (a) In the shown free round-trips the intensity of the reflected beam is approaching 0 for R approaching 1, i.e., detector D_r does not react; (b) However, when an absorbing object is immersed in the liquid (whose refractive index is the same as the one of the crystal in order to prevent losses of the free round-trips), for $R = 0.999$, 99.9% of the incoming beam reflect into D_r, 0.0001% go into D_t and 0.0999% hit the object.

In this paper (in Section 2) we use a monolithic total-internal-reflection resonator which has recently shown extremely high efficiencies in order to construct an optical energy-exchange-free device with an efficiency approaching 100%. Since the device differs from the usual quantum measurement devices, which assume an exchange of at least one quantum of energy [5], it immediately provokes the question whether one carry out a *welcher Weg* interference experiment with its help. In Section 3 we propose such an experiment using atom interferometry.

2. Resonance energy-exchange-free detection

The experiment (see Fig. 1) uses an uncoated monolithic total-internal-reflection resonator (MOTIRR) coupled to two triangular prisms by the frustrated total internal reflection (FTIR) [8,9]. Both MOTIRR and the prisms require a refractive index $n > 1.41$ to achieve total reflection. When we bring prisms within a distance of the order of the wavelength, the total reflection within the resonator will be *frustrated* and a fraction of the beam will tunnel out of and into the resonator. Depending on the dimension of the gap and the polarization of the incidence beam one can well define a reflectivity R within the range from 10^{-5} to 0.99995 [9,10]. Losses for the MOTIRR and FTIR may be less than 0.3%. The incident laser beam is chosen to be polarized perpendicularly to the incident plane so as to give a unique reflectivity for each photon. The faces of the resonator are polished spherically to give a large focusing factor and to narrow down the beam. A cavity which the beam in its round-trips has to go through is cut in the resonator and filled with an index-matching fluid to reduce losses. If there is an object in the cavity, i.e., in the way of the round-trips of the beam in the resonator, the incident beam will be almost totally reflected (into D_r). If there is no object, the beam will be almost totally transmitted (into D_t). 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 of its excellent frequency stability (down to 10 kHz in the visible range) [11].

We calculate the intensity of the beam arriving at the detector D_r when there is no object in the cavity in the following way. The portion of the incoming beam of amplitude $A(\omega)$ reflected at the incoming surface is described by the amplitude $B_0(\omega) = -A(\omega)\sqrt{R}$, where R is the reflectivity. The remaining part of the beam tunnels into the MOTIRR and travel around guided by one FTIR (at the face next to the right prism where a part of the beam tunnels out into D_t) and by two proper total internal reflections. After a full round-trip the following portion of this beam joins the directly reflected portion of the beam by tunnelling into the left prism: $B_1(\omega) = A(\omega)\sqrt{1-R}\sqrt{R}\sqrt{1-R}e^{i\psi}$, where $\psi = (\omega - \omega_{\rm res})T$ is the phase added by each round-trip; here ω is the frequency of the incoming beam, T is the round-trip time, and $\omega_{\rm res}$ is the selection frequency corresponding to a wavelength which satisfies $\lambda = L/k$, where L is the round-trip length of the resonator and k is an integer. Each subsequent round-trip contributes to a geometric progression

$$B(\omega) = \sum_{i=0}^{n} B_i(\omega), \tag{1}$$

where n is the number of round-trips. We lock the laser at ω which is as close to $\omega_{\rm res}$ as possible. Because of the afore-mentioned characteristics of the continuous wave lasers we can describe the input beam coming from such a laser during the coherence time by means of $A(\omega) = A\delta(\omega - \omega_{\rm res})$. The following ratio of intensities of the reflected and the incoming beam then describes the efficiency of the device for free round-trips,

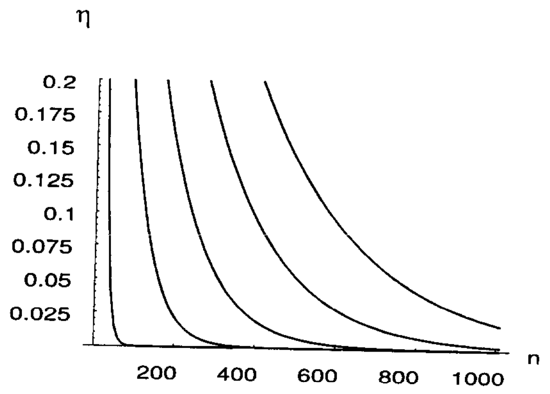

Fig. 2. Realistic values of η for $R = 0.95$ (the lowest curve), 0.99, 0.995, 0.997 and 0.998. The curves represent the sum given by Eq. (2) as a function of the number of round-trips.

$$\eta = \frac{\int_0^\infty B(\omega)B^*(\omega)\,\mathrm{d}\omega}{\int_0^\infty A(\omega)A^*(\omega)\,\mathrm{d}\omega} = 1 - \frac{1-R}{1+R}\left(R^{2n} - 1 + 2\sum_{j=1}^{n}(1+R^{2n-2j+1})R^{j-1}\right). \qquad (2)$$

The expression is obtained by mathematical induction from the geometric progression of the amplitudes (Eq. (1)).

In the experiment one has to lower the intensity of the beam until it is likely that only one photon would appear within an appropriate time window (1 ns–1 ms < coherence time), which allows the intensity in the cavity to build up. The obtained η thus becomes a probability of detector D_r reacting when there is no object in the system. As shown in Fig. 2, η approaches zero after 100 round-trips for $R = 0.95$, after 1000 round-trips for $R = 0.995$, etc., which is all multiply assured by continuous wave laser coherence length. In other words, a response from D_r means that there is an object in the system. In the latter case the probability of the response is R, the probability of a photon hitting the object is $R(1-R)$, and the probability of photon exiting into D_t detector is $(1-R)^2$. By widening the gaps between the resonator and the prisms we can make $R \to 1$ and therewith obtain an arbitrarily low probability of a photon hitting an object. We start each testing by recording the first two or three clicks of D_r or D_t after opening a gate for the incident beam. In this way we allow the beam to "wind up" in the MOTIRR. And when either D_r or D_t fires (possibly even two or three times in a row to be sure in the result) the testing is over. Waiting for several clicks results in a bigger time window, but a chance of a photon hitting an object remains very low. A possible 300 km coherence length does not leave any doubt that a real experiment of detecting objects without transferring a single quantum of energy to them can be carried out successfully, i.e., with an efficiency exceeding 99%. Also detectors might fail to react but this is not a problem because single photon detectors with 85% efficiency are already available and this would again only increase the time window for a few nano seconds what does not significantly influence the result.

Thus we obtain the energy-exchange-free detection device in which the observed particles do not suffer any recoil. With opaque particles bigger than the wavelength of the applied laser beam we have got the maximal efficiency. However, our device can also see smaller objects because the main process in our resonator (which is a kind of Fabry–Perot interferometer) is an interference in which the main role plays a possibility (which need not be realized) of a photon to hit an object in one of the round trips inside MOTIRR. In other words the device "sees" objects which exceed the resolution power of a standard microscope. The efficiency $1 - \eta$ continuously decreases for smaller and smaller objects but that can be significantly improved if we choose the laser beam frequency which would correspond to an atomic resonance frequency of the object. On the other hand, the efficiency would be increased by using plasma X-ray lasers, if one designed an efficient X-ray resonator. For example, the Nd^{3+}:glass laser system at Lawrence Livermore National Laboratory produces 250-ps X-ray laser pulses at wavelengths shorter than 5 nm [12]. Our elaboration in Ref. [6] shows that the resonator would work with 250-ps pulses and the geometrical round path of 4 cm.

3. "Welcher Weg" detection

The experiment (see Fig. 3) uses a combination of atom interferometer with ultracold metastable atoms and the resonance energy-exchange-free path detection by means of a movable MOTIRR (of course, without liquid, which only slightly reduces the effi-

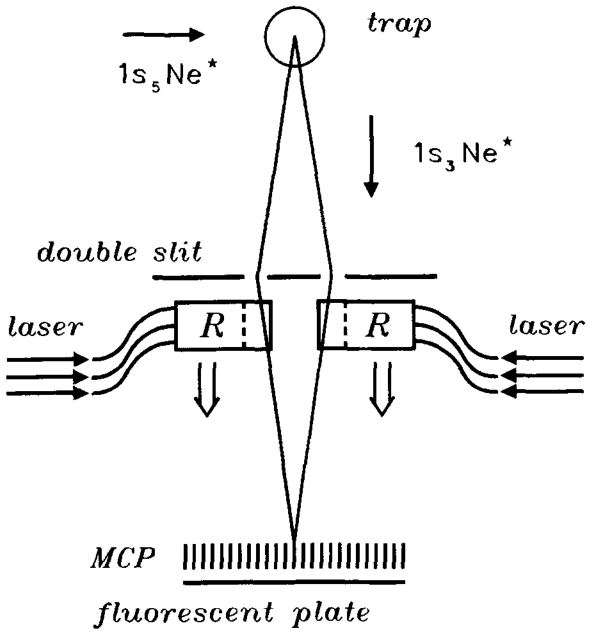

Fig. 3. Proposal for a *welcher Weg* experiment with ultracold atoms. MOTIRR resonators R (see Fig. 1), here shown sideways, move together with the falling atoms which sit in their openings. See Section 3 for other details.

ciency). To increase the probability of an atom being hit by the round tripping beam, the incoming laser beam should be split into many beams by multiple beam splitters, each beam containing in average one photon in the chosen time window, so as to feed the MOTIRR through many optical fibers. As for atom interferometer we adapt the one presented by Shimizu et al. [13] primarily because their method is almost background free. The atom source is a magneto-optical trap containing $1s_5$ neon metastable atoms which are then excited to the $2p_5$ state by a 598-nm laser beam. Of all the states to which $2p_5$ decays we follow only $1s_3$ atoms whose trajectory are determined only by the initial velocity and gravity (free fall from the trap). (Other states are either trapped by the magnetic field of the trap, or influenced and dispersed by another 640-nm cooling laser beam.) Now the atoms fall with different velocities but each velocity group forms interference fringes calculated as for the optical case and only corrected by a factor which arises from the acceleration by the gravity during the fall. The MOTIRR is mounted on a device which follows (with acceleration) one velocity group from the double slit to microchannel plate detector (MCP). (Atoms from other groups move with respect to the MOTIRR and therefore – because of their small cross section – cannot decohere the MOTIRR.) The laser is tuned to a frequency equal to the $1s_3$ resonance frequency. The most distinguished fringes has the group which needs 0.1 s to reach MCP from the double slit and are accelerated to 2 m/s. The source is attenuated so much that there is in average only one atom in a velocity group. The whole process repeats every 0.4 s. Assuming that we have 10 ns recovery time for the photon detectors and 300 optical fibers we arrive at about 10^7 counts which all go into one detector D_t when no atom obstructs a round trip. (For reflectivity $R = 0.999$ the probability of the D_r being activated is 2×10^{-9}.) As soon as D_r detector fires we know which slit the observed atom passed through. (The probability of photon hitting an atom is 0.001. In order to be able to estimate how many photons fired D_r we can use *photon chopping* developed by Paul et al. [14].) After 10^3 repeating of such successful detections we have enough data to see whether the interference fringes are destroyed significantly with respect to unmonitored reference samples or not.

4. Discussion

In Section 2 we presented a device (derived from Paul and Pavičić's device [6]) for a photonic detecting of objects without an energy exchange. More precisely, there is a very high probability approaching 100% that not even a single photon energy $h\nu$ will be transferred to the objects. Figuratively, one could call the device a "Heisenberg microscope without a kick". In Section 3 we employed the device in the *welcher Weg* detection of the atoms taking part in an interference experiment. Both, the Heisenberg microscope reasoning and arguments against a *welcher Weg* experiment traditionally rest on the Heisenberg uncertainty relations. Uncertainty relations always refer to the mean values of the operators and that means – even when the operators are projectors – statistics obtained by recording an interaction, i.e., by a reduction of the wave packet. In our *"energy-exchange-free microscope"* measurement (Section 2) we do not attach any value to any operator in the Hilbert space description of the observed systems and therefore, *no* uncertainty relation is involved. As for the *welcher Weg* experiment (Section 3) it has recently been shown that "it is possible to obtain *welcher Weg* information without exposing the interfering beam to uncontrollable scattering events. . . . That is to say, it is simply the information contained in a functioning measuring apparatus that changes the outcome of the experiment and not uncontrollable alterations of the spatial wave function, resulting from the action of the measuring apparatus on the system under observation." [15] There is, however, an essential difference between our proposal and the ones by Scully, Englert, and Walther [15] (microwave cavity proposal), by Sanders and Milburn [16] (quantum nondemolition measurement with the Kerr medium) and by Paul [17] (perfectly reflecting mirror proposal). In all of them there is slight exchange of energy which does not significantly disturb the spatial wave function of the system taking part in the interference but does disturb its phase. In our proposal we apparently have no exchange of energy. We say "apparently" because in a future real experiment we should discuss the Bohrian physical process responsible for disappearance of the interference fringes in detail.

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