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 exper-
iment with an atom interferometer is proposed. The obtained results are in
agreement with quantum theory.

PACS: 03.65.Bz, 42.25.Hz, 07.60.Ly, 42.50.Vk

Keywords: Interaction–free experiment; “Welcher Weg” experiment; Uncer-
tainty relations; Back–action–free experiment
I. 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. [1] 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. Mach–Zehnder interferometer itself cannot be used for practical energy–exchange–free measurement because of its very low efficiency (under 30%). Therefore Paul and Pavlić [6] recently proposed a very simple and easily feasible energy–exchange–free experiment based on the resonance in a single cavity which efficiency can realistically reach 95%. As a resonator the proposal used a coated crystal which however reduced its efficiency.

In this paper (in Sec. II) 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 [3], it immediately provokes a question whether one carry out a welcher Weg interference experiment with its help. In Sec. III we propose such an experiment using atom interferometry.

1 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. . . . These conditions must be considered as an inherent element of any phenomenon to which the term “[interaction]” can be unambiguously applied.” [7]
II. 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 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 reflectivity \( R \) within the range from \( 10^{-5} \) to 0.99995. [9,10] Losses for 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 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 reflectivity. The remaining part of the beam tunnels into 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 \( \psi = (\omega - \omega_{\text{res}})T \) is the phase added by each round–trip; here \( \omega \) is the frequency of the incoming beam, \( T \) is the round–trip time,
and $\omega_{res}$ 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

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

where $n$ is the number of round-trips. We lock the laser at $\omega$ which is as close to $\omega_{res}$ 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 $A(\omega) = A\delta(\omega - \omega_{res})$. The following ratio of intensities of the reflected and the incoming beam then describes the efficiency of the device for free round-trips:

$$\eta = \frac{\int_{0}^{\infty} B(\omega)B^*(\omega)d\omega}{\int_{0}^{\infty} A(\omega)A^*(\omega)d\omega} = 1 - \frac{1 - R}{1 + R} \left[ R^{2n} - 1 + 2 \sum_{j=1}^{n} (1 + R^{2n-2j+1})R^{j-1} \right].$$

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 ($1\text{ns} - 1\text{ms} < \text{coherence time}$) what allows the intensity in the cavity to build up. The obtained $\eta$ thus becomes a probability of detector $D_r$ reacting when there is no object in the system. As shown in Fig. 2, $\eta$ 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 $R \rightarrow 1$ 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 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 the 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, 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 Paul 
and Pavičić [8] shows that the resonator would work with 250–ps pulses and the geometrical 
round path of 4 cm.

III. ‘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 what only slightly reduces the efficiency). 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 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\textsubscript{5} neon metastable atoms which are then excited to the 2p\textsubscript{5} state by a 598–nm laser beam. Of all the states to which 2p\textsubscript{5} decays we follow only 1s\textsubscript{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. 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 MOTIRR and therefore—because of their small cross section—cannot decohere MOTIRR). The laser is tuned to a frequency equal to the 1s\textsubscript{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\textsuperscript{7} counts which all go into one detector D\textsubscript{r} when no atom obstructs a round trip. (For reflectivity $R = 0.999$ the probability of $D_r$ being activated is $2 \cdot 10^{-9}$.) 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, Törmä, Kiss, and Jex [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.
IV. DISCUSSION

In Sec. II, 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 Sec. III, 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 (Sec. II), 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 (Sec. III), 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 [13] (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.
I thank Harry Paul for many discussions and suggestions. I acknowledge supports of the Alexander von Humboldt Foundation, Germany, the Max–Planck–Gesellschaft, Germany, and the Ministry of Science of Croatia.
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FIGURES

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.

FIG. 2. Realistic values of \( \eta \) 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.

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 Sec. 11 for other details.
Fig. 1
Fig. 3