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Experiment on interaction-free measurement in neutron interferometry

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Abstract

A neutron interferometric test of interaction-free detection of the presence of an absorbing object in one arm of a neutron interferometer has been performed. Despite deviations from the ideal performance characteristics of a Mach-Zehnder interferometer it could be shown that information is obtained without interaction. © 1997 Elsevier Science B.V.

1. Introduction

In classical mechanics the interaction between a measuring device and the object is treated as arbitrarily small and can therefore be neglected. This is fundamentally different in quantum physics, as exemplified in the Heisenberg microscope: A measurement of the position of an electron inevitably leads to a disturbance of its momentum by the scattering of a photon. It seems that no measurement can be performed without the interaction with a particle. Even in the case investigated by Dicke [1], where knowledge about the position of an atom is gained by ascertaining where it is not, it had to be concluded that photon scattering still is responsible for providing the information. However, the scattering remains unresolvable, because the change in the photon's momentum is within the momentum uncertainty of the illuminating beam of light. But recently Elitzur and Vaidman (EV) proposed an experiment where the presence of a perfectly absorbing classical object in one arm of a Mach-Zehnder interferometer can be detected [2-5]. EV symbolized the object by a bomb which explodes when the measuring particle hits it. Their scheme is shown in Fig. 1. Here, no interaction is involved. For, had there been an interaction, the test particle would have been absorbed and could not have reached any of the detectors at the outputs of the interferometer.

The drawback of this scheme is that even when adjusting the transmissivity of the beam splitters of the interferometer, the probability of recognizing the object without interaction does not exceed 50%. This disadvantage could be overcome by Zeilinger et al., who introduced a multi-loop interferometer. In the limit of infinitely many loops, one can obtain a probability of 100% of determining the presence of the absorbing object without interaction [6]. Paul and Pavicic incorporated this idea into a proposal employing an optical resonator [7]. A first experiment with polarized photons has already been reported [8,9]. Owing to imperfections of the optical devices only around 50% of

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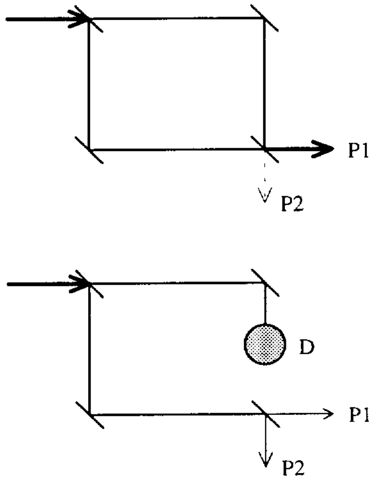

Fig. 1. (a) The test particle will exit the interferometer at P1 when there is no object, or a perfectly transparent one, in one path of the interferometer. (b) With the perfectly absorbing object D in one path, the test particle, if it is not absorbed, can exit at P1 as well as at P2.

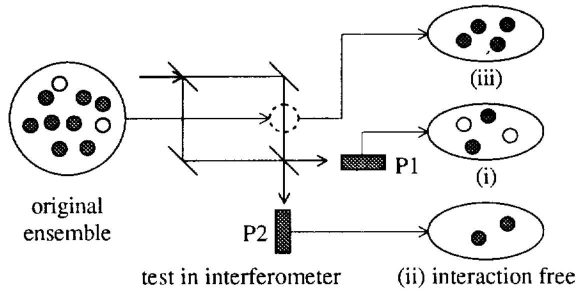

Fig. 2. An original ensemble of black and transparent objects can be separated into three groups by a test in the interferometer. The black objects in group (ii) get there without having interacted with the test particle.

interaction-free detections of the object were possible. The theoretical analysis of these situations has also been extended to absorbing *quantum* objects, where it is no longer possible to assume a perfect absorber. But even then, a sizable amount of knowledge is gained without interaction [10,11].

In this Paper we report on the first experiment with neutrons. The original scheme of EV was implemented in a single crystal neutron interferometer. Although such interferometers are not ideal Mach-Zehnder interferometers, it was possible to ascertain the presence of an absorbing object, which was realized as a neutron detector, with higher probability than classical physics would permit, so that one must conclude that some knowledge is obtained without interaction. Before dealing with the details of this experiment, it is useful to recall the ideal case of EV (Fig. 1).

The two interferometric paths have equal length and the beam splitters at the entrance and at the exit have the same reflectivity of 50%. When the interferometer is empty the probability amplitudes leading to P1 interfere constructively, while those leading to P2 interfere destructively. Therefore a particle will always be directed towards P1 (Fig. 1a). If a perfectly absorbing object — from now on called a black object — is inserted into one path of the interferometer, only one beam can reach the exit ports, because the wave function behind the object vanishes. No interference can occur. With semitransparent mirrors at the entrance and exit of the interferometer, there is a probability of 50% that the particle will be absorbed in the object, and a probability of 25% each that it will reach either P1 or P2.

In order to clarify why an interaction-free measurement is involved here, consider a collection of identically looking objects, some perfectly absorbing, some perfectly transparent (i.e., not even inducing a phase shift) for the kind of particles used in the interferometer. Will it be possible to separate the objects into the two classes when testing them in the interferometer? Classically there is no way. Without permitting interaction we could only randomly pick out objects and put them into the one or the other class. But quantum mechanically a separation is possible. This is illustrated in Fig. 2. Suppose we place one such object, of which it is not known whether it is black or transparent, into one path of the interferometer and send one particle. Three different outcomes can occur:

(i) The particle is detected at port P1. This can happen in either case, so no information is gained and another particle may be used.

(ii) The particle is detected at port P2. This is impossible with a perfectly transparent object, so we know now, that a black object is in the interferometer. Only one particle entered the interferometer and it was not absorbed, but was detected at P2. So it cannot have interacted with the object, and we got information of the absorbing property of the object *without interaction*.

(iii) The particle is detected neither at P1 nor at P2. Here we conclude that the particle was absorbed by a black object, which, clearly, involved an interaction.

The result in (ii) is a nice example of the wave–particle duality. The wave description determines the probabilities of the detection at the ports P1 and P2 by interference of the wave functions of the two paths. The particle description lets us conclude, that the particle *did not interact* with the black object when it was detected at P2: If it had been at the site of the black object, it would have been caught there, and could not have reached P2.

The three outcomes permit putting the tested objects into three groups as sketched in Fig. 2. Groups (ii) and (iii) will only contain black objects. All transparent objects are accumulated in group (i), but also some black objects, because in a single test the probability for a transparent object to be placed there is 100%, while for a black object it is 25%. With repeated tests of the objects of this group, the probability of still having a black object there will approach zero. Simultaneously, the number of objects in group (ii) will reach one third of the originally available black objects. Two thirds of the black objects will end up in group (iii), because they interacted with the test particle and absorbed it.

The purpose of the present experiment was to perform such a selection procedure with a real neutron interferometer. The black objects were realized as a neutron detector. In this manner the three possible outcomes of an individual test could be observed. For transparent objects the interferometric paths were left empty.

2. Experiment and results

The experiment was performed with the perfect-silicon crystal neutron interferometer installed at the north beam port of the 250 kW TRIGA MARK II reactor of the Atominstitut. This interferometer separates the paths by about 4 cm and recombines them again. The action of semitransparent mirrors is accomplished through Bragg diffraction in Laue geometry at the 220-planes of the four crystal slabs. As can be seen in Fig. 3, the basic layout is similar to a Mach–Zehnder interferometer and therefore well suited to test the EV scheme. The main difference to the ideal case is that the two output beams are not equivalent. Output beam 1 can have a contrast of 100% (i.e., be fully modulated), but output beam 2 cannot [12], because the number of reflections and transmissions at the crystal slabs is not the same for the two paths constituting the output beam 2. But due to crystal imperfections, even output beam 1 never reaches a contrast of 100%. A contrast of 40% is obtained with a cross section of 4 mm (width) times 7 mm (height) of the incident beam, and a wavelength of $\lambda = 1.8$ Å with a spread of $\Delta\lambda/\lambda \approx 1\%$. When normalizing the average intensity at output 1 to 1, the intensities of our setup are, as a function of a phase shift ϕ between paths I and II (setup as shown in Fig. 3, but without the Cd sheet and without an object in path I),

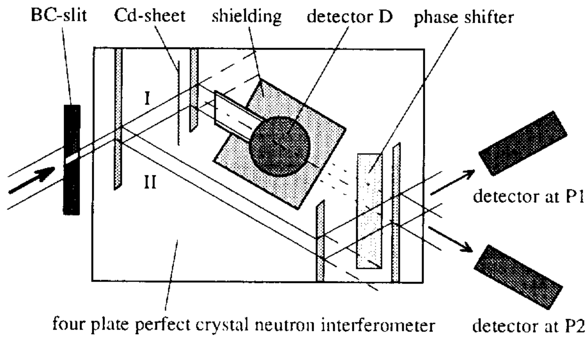

Fig. 3. Experimental scheme. The base area of the four plate interferometer is 144 mm × 100 mm. Crystal slabs, phase shifter, black object (= detector D plus shielding) and beam widths are drawn to scale. The wide incident beam is collimated by a boron carbide (BC) slit. The transmitted part of beam I after the second crystal slab and that of beam II after the third crystal slab leave the interferometer unused. Detectors at exit beams P1 and P2 not to scale.

$$I_1(\phi) = 1 + 0.4\cos(\phi) \qquad (1)$$

$$I_2(\phi) = 1.7 - 0.4\cos(\phi). \qquad (2)$$

There is no phase shift ϕ at which one of the output beams is completely dark. This is contrary to the crucial assumption in the EV scheme. Consequently, a statement of the sort "if a neutron is detected at P2, a black object is with certainty in one of the arms of the interferometer" was no longer possible. Nevertheless each test had to lead to a decision into which group the tested object should be put. We kept the three groups outlined above. But the certain identification of black objects had to be replaced by a probabilistic one, and it was attempted to achieve an enrichment of transparent objects in one group and of black objects in the two other groups. For this purpose theoretical simulations were undertaken, using the performance characteristics of the actual interferometer [13]. The questions to be answered were: Could the probability of successful interaction-free identification of black objects be increased by

(a) attenuating the intensity of beam I, into which the test objects were to be placed, with an additional partial absorber, and

(b) introducing an additional constant phase shift of π, such that a registration of a neutron at P1 rather than at P2 could be taken to indicate the presence of a black object.

It turned out that the optimal conditions could be obtained when attenuating beam I to $t = 16\%$ of its original intensity. This would reduce the amplitude of the intensity oscillations at P1 and P2 as a function of ϕ by a factor $\sqrt{t} = 0.40$. The attenuation was done with a Cd-sheet of 125 μm thickness, which was placed in front of the second crystal slab, and parallel to this slab, as shown in Fig. 3. The actual transmittance of this sheet was 0.158(4). The simulation also showed, that the phase shift between beams I and II should remain zero, just as in the EV scheme, in such a manner that the count rate at P1 is at the *maximum* when a transparent object, or none, is present at the test position. But this still made it necessary to set the aluminum phase shifter to a certain value, because contrary to the ideal case, the actual interferometer has an internal phase offset due to inaccuracies of slab thicknesses and distances. In the experiment the registration of a neutron at P1 was interpreted as the presence of a transparent object, while registration at P2 was taken to indicate a black object.

The probabilities of the possible results were determined by measuring the intensities of the neutron beams at the detectors P1 and P2, and, when applicable, at the detector D, which constituted the black object. The measured intensities of a typical run are listed in Table 1 below. Averaging over several runs was not done, because they showed different contrast, depending on the vibrational level of the building. A run lasted for approximately four hours, during which measurements with and without the black object in path I, as well as background measurements and normal interference scan measurements had to be taken (see Ref. [13], p. 61). Without any object in the paths, but with the attenuating Cd-sheet in place (Fig. 3), the total intensity of P1 *plus* P2, including background, was 1.25 counts/s.

Table 1
Observed neutron counts with transparent (i.e., none) or black object in the test position

Detector	Transparent object	Black object	Background
P1	3561	2073	215
P2	793	999	59
D	—	2253	1422

The background was determined by rotating the interferometer crystal around the vertical axis away from the Bragg condition by some 3 degrees, so that the incident neutron beam went straight through the first and second crystal slabs. The background at D is due to its position close to the incident beam, whose intensity is three orders of magnitude larger than the intensity which the Bragg condition selects for the interferometer. The background at D is in part also due to the gamma radiation which is created when neutrons are absorbed in the Cd-sheet in a nuclear reaction. The detectors P1 and P2 were standard BF_3-filled (atmospheric pressure) cylindrical neutron detectors with a diameter of 5 cm and a length of around 40 cm, and were hit axially by the respective beams. Their efficiencies exceeded 97%. The detector D, representing the black object, had an efficiency of only 65%. Its outside diameter was 2.54 cm, and its length some 30 cm. When at the test position, beam I hit it perpendicular to the axis of the cylinder. It was filled with four atmospheres of He^3. The capture cross section of a thermal neutron at a He^3 nucleus is 5330 barns. This results in a probability of 0.76 that a neutron will be captured in the gas. The reduction to 0.65 is due to averaging over the beam cross section and to electronic discrimination, which was needed to suppress the unwanted gamma-background as much as possible. If the neutron went through detector D unaffected, it was certainly absorbed by the shielding material behind the detector. Thus it was insured that the black object really was black.

From the data in Table 1 it is possible to infer whether an actual interaction-free identification of black objects is possible. In so doing we will assume 100% efficiency of detectors P1 and P2. Since this is not very different from their actual efficiency the resulting error will be small. Detector D of the black object is not needed for the analysis. This detector only

Table 2
Probabilities of detection of a neutron at one of the detectors with black or transparent object in test position. Standard deviations include only Poisson statistics of the counts of Table 1. Numbers in rectangular brackets are probabilities for an ideal Mach-Zehnder interferometer

Object	Detection at P1 (i)	Detection at P2 (ii)	Absorption in object (iii)
black	0.455 ± 0.014 [0.25]	0.231 ± 0.009 [0.25]	0.314 ± 0.018 [0.50]
transparent	0.820 ± 0.020 [1]	0.180 ± 0.008 [0]	—

served for a check of the consistency of the results.

After subtracting the background counts, which is permissible, because they can in principle be made arbitrarily low with improved shielding and electronics, the probabilities for an object to be put into one of the three groups after a test with only a single particle, can be calculated as given in Table 2.

It is noteworthy, that the probability that the neutron gets absorbed in the black object is significantly lower than in an ideal Mach-Zehnder interferometer. This improved performance is also retained in the limit of infinitely many tests of the objects remaining in group (i). In such a procedure, the probability for a black object *not to interact* with the neutron and ultimately to be put into group (ii) is given by

$$p_{\text{black}}^{(\text{ii})} \sum_{n=0}^{\infty} [p_{\text{black}}^{(\text{i})}]^n \approx 0.424, \quad (3)$$

where we have inserted from Table 2, $p_{\text{black}}^{(\text{i})} = 0.455$ and $p_{\text{black}}^{(\text{ii})} = 0.231$. Correspondingly, the probability that the black object ultimately absorbs a particle in this procedure and thus is put into group (iii) is $1 - 0.424 = 0.576$. But, unfortunately, in such repeated tests the transparent objects, too, will accumulate in group (ii). The reason is, that their probability of being put into group (i) in a single test is less than 1, namely $p_{\text{trans}}^{(\text{i})} = 0.820$, according to Table 2. Therefore, when testing objects in group (i) again and again, until either P1 or D fires, all transparent objects and 42.4% of the black objects will end up in group (ii).

A closer analysis reveals that with our real neutron interferometer, the best separation of black and transparent objects is obtained when testing each object *only once*. Then one can obtain a separation as shown in Fig. 4. The x-axis represents the fraction of black objects in the original ensemble. The full curves going from the lower left to the upper right corner represent the fraction of black objects ending up in group (ii),

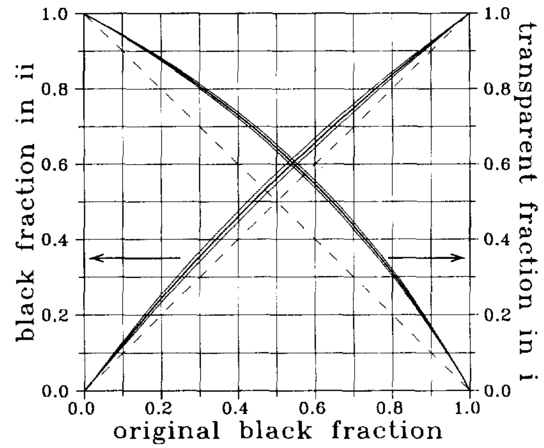

Fig. 4. Results of experiment. Full lines (mean, and plus minus one standard deviation): In a single test of each object, a black object is more likely to be put into group (ii), unless the neutron is absorbed by it in an interaction, while a transparent object is more likely to be put into group (i). Dashed lines: What could be achieved when randomly putting objects of the original ensemble into different groups.

which is the group where the tested object is put when the particle is detected at P2. The thick line is the most likely value, the two thin ones delimit its standard deviation. The dashed line indicates "no separation" of black and transparent objects. One notes that an enrichment of black objects in group (ii) does happen, because their fraction there is always larger than their fraction in the original ensemble. For instance, for a fraction of 0.5 of black objects in the original ensemble, their fraction in the final ensemble (ii) will be 0.562 ± 0.014. Therefore, even with a neutron interferometer, whose performance is far from an ideal Mach-Zehnder interferometer, and in fact far from the best available neutron interferometers, *some information* is obtained in an interaction-free manner. For the sake of completeness Fig. 4 also shows the fraction of transparent objects in group (i) after a single test. These are the curves extending from the upper left to the lower right corner. As expected, transparent objects are accumulated in group (i).

It is also interesting to ask whether for the *real* neutron interferometer there exists a method, different from the EV method, which permits arbitrarily good separation of transparent and black objects. This is indeed possible, albeit at the cost of only a tiny fraction of the originally available black objects remaining. The method consists in repeated tests of the objects in *group (ii)*. As before, let $p^{(ii)}_{\text{black}}$ and $p^{(ii)}_{\text{trans}}$ denote the probabilities that a black, respectively transparent, object will be put into group (ii) after a single test. According to Table 2 we have, again neglecting experimental uncertainties, $p^{(ii)}_{\text{black}} = 0.231$ and $p^{(ii)}_{\text{trans}} = 0.180$. When testing objects of group (ii) a further $N - 1$ times, a black object of the original ensemble is therefore $(p^{(ii)}_{\text{black}}/p^{(ii)}_{\text{trans}})^N = (1.283)^N$ times more likely to remain in group (ii) as compared to a transparent object of the original ensemble. Arbitrarily good purification of group (ii) is therefore possible *without interaction*. The number of black objects group (ii) contains in the end, will however only be $(p^{(ii)}_{\text{black}})^N$ times the number of black objects in the original ensemble.

3. Conclusion

We have performed a test of interaction-free measurement with a neutron interferometer of the Mach–Zehnder type. In the unobstructed interferometer the probability of a neutron to be found in the path of the test position for the black and the transparent objects to be identified was around 0.3, and correspondingly the probability to find it in the other path was around 0.7. The visibility contrast at the exit port P1 only reached around 40%. With such strong deviations from the characteristics of an ideal Mach–Zehnder interferometer it was nevertheless possible to show that an original ensemble with unknown proportions of black and transparent objects can be separated into two groups by testing each object with essentially only one neutron (about 1.04 neutrons on average), which must not be absorbed in the test object. Then one of these groups is guaranteed to contain a higher proportion of black objects than the original ensemble. The black objects are laid out as a neutron detector plus absorptive shielding. A neutron interacting with a black object would certainly be absorbed by it. Therefore, the result shows interaction-free measurement at work.

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