Quantized self-intervening detector networks

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A range of quantum optics experiments is discussed in which the apparatus can be modified by detector outcomes during the course of any run. Starting with a single beamsplitter network, we work our way through a series of more complex scenarios, culminating with a proposed self-intervening experiment which could provide evidence for the existence of the Heisenberg cut, the supposed boundary between classical and quantum physics.

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I. INTRODUCTION

Many quantum experiments involve time-independent apparatus. By this we mean that for each run of such an experiment, the apparatus which prepares the initial state, shields it from the environment during that run and detects the outcome state is classically determined and fixed. Such experiments will be called Type 1. In quantum optics, double-slit, Mach-Zehnder, and quantum eraser experiments [1] are of this type. So too are high energy particle scattering experiments such as those conducted at the LHC in CERN. Type 1 experiments are important because they allow the focus of attention to be entirely on the dynamical evolution of states of SUOs (systems under observation), normally regarded as the prime objective of SQM (standard quantum mechanics). SQM generally describes Type 1 experiments via time-independent Hamiltonians.

A second class of experiment, referred to here as Type 2, involves some time-dependence in the apparatus, such that any changes in the apparatus during a run are controlled externally, either by the experimentalist or by environmental factors. Spin-echo magnetic resonance experiments are of this type, because the experimentalist arranges for certain magnetic fields to be rotated precisely whilst additionally, the environment introduces random external influences related to local temperature. An example of random changes controlled by the experimentalist are delayed-choice experiments such as that of Jacques et al [2], where carefully arranged random changes are made during each run. SQM typically describes such experiments via time-dependent Hamiltonians.

Type 2 experiments are more interesting than Type 1 because they have the potential to reveal more information about the dynamics of SUOs than Type 1. Schwinger’s source theory shows that in principle, Type 2 experiments allow for the extraction of all possible information about quantum systems [3]. Type 1 and Type 2 experiments may be collectively labelled as endophysical, because all classical apparatus interventions are external in origin. In such experiments, the apparatus is classically well defined at each instant of time during each run, even in those situations where it changes randomly. Therefore, a classical block universe [4] account of apparatus during each run of a Type 1 or 2 experiment is possible.

In this paper we explore a third type of quantum experiment, which we label Type 3, or endophysical. In such experiments, the apparatus is modified internally by the quantum dynamics of the SUO, rather than externally by the observer or the environment. An interesting question which we shall address towards the end of this paper is whether Type 3 experiments can always be given a classical block universe account or whether something analogous to superpositions of different apparatus has to be envisaged (not to be confused with superpositions of states of SUOs).

This question is related to the rules of quantum information extraction as they are currently known in SQM. These rules state that quantum interference can occur in the absence of classical which-path information, the most well-known example of this being the double-slit experiment. The question here is what precisely does a lack of which-path information mean: if such as thing as a photon passed through one of the slits, would it leave any trace in principle? Even if it did, it might be believed that any such interaction a photon had with atoms at either slit would be on the quantum level, far below the scales of classical mechanical detection, and so the observer of the interference pattern would simply be unaware of such interaction. This seems wrong to us on two counts: first, there is now sufficient evidence against the notion that photons are particles in the conventional sense [5] and second, one observer being unaware of actual which-path information held by another observer could not by itself induce interference patterns. There has to be something deeper than that in the origin of quantum interference.

The neutron interference experiment discussed by Greenberger and YaSin [6] explores this question by moving towards larger scales of interaction between SUO and apparatus. In their experiment, the movement of mirrors involved in their quantum erasure scheme involves a macroscopic numbers of atoms and molecules [7]. In this case, the dynamical effects of the impact of a particle on a mirror is reversed by a second impact. What is amazing is the idea that all possible traces of the first impact could be completely erased, even though there could (in principle) be time for information from the first impact to be dissipated into the environment, thereby rendering the process irreversible.

We take this line of thinking one step further. One of
the experiments we propose and discuss here appears to involve the superposition of states of different beamsplitters, which are macroscopic pieces of apparatus. At least one of these beamsplitters has to be triggered if any interference effects are observed, but that observation cannot occur if the information as to which beamsplitter is involved can be extracted by the observer. If such an experiment were carried out and quantum interference observed, then the implications would be that quantum principles apply to apparatus as well as states of SUOs, thereby demonstrating that the laws of quantum information are truly universal.

We focus exclusively on linear quantum evolution, i.e., one conforming with the principles of SQM as discussed for example in [8], rather than appeal to any form of nonlinear quantum mechanics to generate self-intervention effects. We explore a number of Type 3 thought experiments involving photons, which act as either quantum or classical objects at various times. As quantum objects they pass through beam-splitters and suffer random outcomes as a result. As classical objects they are used to trigger the switching on or off of macroscopic apparatus, a switching which determines the subsequent quantum evolution of other photons. We shall not discuss the nature of photons per se, except to say that they are referred to as particles for convenience only: our ideology and formalism treats them as signals in elementary signal detectors (ESDs) [9]. Everything is idealized here, it being assumed that all detectors operate with one hundred percent efficiency and that photon polarizations and wavelengths can be adjusted wherever necessary to make the scenarios discussed here physically realizable. The experiments we discuss are not necessarily based on photons: other particles such as electrons could be used in principle. We use the Schrödinger picture throughout, using a Hilbert space quantum register of sufficiently many qubits to model all information exchange requirements. In our notation, $bc$ denotes a two photon signal state, equivalent to $|b\rangle \otimes |c\rangle$ in standard notation and to $A^+_b A^+_c |0\rangle$ in [2], where $|0\rangle$ is the void or “no-signal” state of the apparatus and $A^+_b$ is a signal operator creating a positive signal state at ESD $b$. Capital letters such as $E_1$ represent complex outcome probability amplitudes.

II. EXPERIMENT 1: BASIC SELF-INTERVENTION

To illustrate the sort of experiment we are interested in, we start with the basic experiment shown schematically in Figure 1. A correlated, non-entangled two photon state $\Psi_0 \equiv bc$ is created by source $A$. Such states can be created by parametric down conversion and suitable filtering. Photon $c$ is subsequently passed through beamsplitter $D$ and emerges in state $d_1$ or $d_2$ with amplitudes $D_1$ and $D_2$ respectively, such that $|D_1|^2 + |D_2|^2 = 1$. If ESD $d_1$ is triggered rather than ESD $d_2$, then a macroscopic mechanism triggers beamsplitter $E$ to be activated. In all diagrams, squares denote apparatus modules such as sources of photon pairs and beamsplitters, circles denote ESDs and single lines denote optical pathways. Dotted double lines denote signal detection followed by classical switching on of apparatus.

Photon $b$ meanwhile is sent over a sufficiently long optical path to ensure that photon $c$ has been detected in one of the ESDs $d_1$ or $d_2$. Only then does $b$ enter that part of the apparatus which has been prepared by the outcome of beamsplitter $D$. If the outcome was $d_1$, then $b$ enters beamsplitter $E$ and emerges in state $e_1$ or $e_2$ with amplitude $E_1$ and $E_2$ respectively, such that $|E_1|^2 + |E_2|^2 = 1$. On the other hand, if the outcome at $D$ was $d_2$, then $E$ is not switched on, so that $b$ is unaffected and gets registered as an unaltered photon $b$.

The labstate $|\Psi_1\rangle$ just before any photons are detected is given by

$$
\Psi_1 = D_1(E_1e_1 + E_2e_2)d_1 + D_2bd_2.
$$

(1)

In (1), photon $d_1$ is included in the state explicitly. This is because although it is necessarily absorbed during the switching on of beamsplitter $E$, the observer can determine the fact that that switching has occurred, and this is equivalent to the detection of a photon by an ESD. In our formalism, ESDs are any processes which result in classical signal information being extracted from a quantum state. As stated above, we think of photons not as particles but as quanta of information.

From (1) we can immediately read off the three possible non-zero outcome probabilities:

$$
P(c_1kd_1) = |D_1|^2 |E_1|^2, \quad P(c_2kd_1) = |D_1|^2 |E_2|^2,
$$

$$
P(bkd_2) = |D_2|^2,
$$

(2)

which sum to unity as required.

III. EXPERIMENT 2: DOUBLE SELF-INTERVENTION

The next variant experiment is shown in Figure 2. Now photons $b$ and $c$ pass through beamsplitters $E$ and $D$ respectively. If detected, outcome $d_1$ of $D$ switches on beamsplitter $F$, whereas if detected, outcome $d_2$ of $D$ switches on beamsplitter $G$.

The dynamics is calculated as follows. The initial lab-state is $\Psi_0 = bc$. Subsequently, we have $b \rightarrow (E_1e_1 +$
between photons sufficiently long optical paths so as to allow interference and so on. None of these probabilities demonstrates any correlation would have to be arranged. Provided this is the case, this interference essentially involves waves from different sources.

For the next stage, we refer to Figure 2 to write down the following substage evolution rules:

\[
\begin{align*}
E_1(1) & \rightarrow (F_1 f_1 + F_2 f_2) d_1, \\
E_2(2) & \rightarrow (G_1 g_1 + G_2 g_2) d_2, \\
E_3(3) & \rightarrow (H_1 h_1 + H_2 h_2) d_3, \\
E_4(4) & \rightarrow (I_1 i_1 + I_2 i_2) d_4, \\
E_5(5) & \rightarrow (J_1 j_1 + J_2 j_2) d_5.
\end{align*}
\]

(3)

where \(|E_1|^2 + |E_2|^2 = |G_1|^2 + |G_2|^2 = 1\). This gives

\[
\Psi_2 = E_1 E_2 E_3 E_4 E_5 (F_1 f_1 + F_2 f_2) d_1 E_1 E_2 E_3 E_4 E_5 (G_1 g_1 + G_2 g_2) d_2 E_1 E_2 E_3 E_4 E_5 (H_1 h_1 + H_2 h_2) d_3 E_1 E_2 E_3 E_4 E_5 (I_1 i_1 + I_2 i_2) d_4 E_1 E_2 E_3 E_4 E_5 (J_1 j_1 + J_2 j_2) d_5.
\]

(4)

From this we immediately read off six non-zero correlation probabilities, such as \(P(f_1 \& d_1) = |E_1|^2 |D_1|^2 |F_1|^2\), and so on. None of these probabilities demonstrates any quantum interference, because complete which-path information is available in each case.

IV. EXPERIMENT 3: INTERFERING SINGLE SELF-INTERVENTION

The third scenario is shown in Figure 3. In this case, the initial photon pair is passed through a pair of beamsplitters exactly as in Experiment 2. The difference lies in the next stage. Photons \(e_1\) and \(d_2\) are sent off over sufficiently long optical paths so as to allow interference between photons \(e_2\) and \(d_1\) in beamsplitter \(F\). Note that this interference essentially involves waves from different sources, including photons \(b\) and \(c\), so phase and wavelength matching would have to be arranged. Provided this is the case, the dynamics is given by

\[
\begin{align*}
e_1 d_1 & \rightarrow e_1(F_1 f_1 + F_2 f_2) d_1, \\
e_1 d_2 & \rightarrow e_1 d_2, \\
e_2 d_2 & \rightarrow (F_3 f_3 + F_4 f_4) d_2, \\
e_2 d_1 & \rightarrow e_2 d_1
\end{align*}
\]

(5)

where the coefficients \(\{F_i\}\) satisfy the relations

\[
|F_1|^2 + |F_2|^2 = |F_3|^2 + |F_4|^2 = 1, \quad F_1 F_3^* + F_2 F_4^* = 0.
\]

(6)

From which we read off the non-zero probabilities

\[
\begin{align*}
P(f_1 \& g_1) & = |E_1 D_1 F_1 G_1 + E_2 D_2 F_3 G_3)|^2, \\
P(f_1 \& g_2) & = |E_1 D_1 F_2 G_2 + E_2 D_2 F_4 G_4)|^2, \\
P(e_1 \& f_2) & = |E_1 D_1 F_3 G_2 + E_1 D_1 F_4 G_3)|^2, \\
P(e_2 \& f_2) & = |E_2 D_2 F_3 G_1 + E_2 D_2 F_4 G_1)|^2, \\
P(d_2 \& f_2) & = |E_2 D_2 F_3 G_2 + E_2 D_2 F_4 G_4)|^2.
\end{align*}
\]

(7)

These probabilities sum to unity as required.
In this variant experiment, two of the outcome probabilities, \(P(f_1 & g_1)\) and \(P(f_1 & g_2)\) show interference. This interference has essential contributions from beamsplitters \(F\) and \(G\) in a manner which seems impossible to explain in terms of photons as classical particles.

In all experiments where quantum interference takes place, there inevitably has to be some which-path uncertainty somewhere. This does not occur in variant experiments 1 or 2 but does occur in variant 3.

The results can be simplified somewhat by assuming each beamsplitter is symmetric, i.e., \(|E_1| = |E_2| = 1/\sqrt{2}\). etc. There is a well-known change of phase due to reflection at a beamsplitter, relative to the transmitted beam \[10\]. If we take \(D_1 = E_1 = F_1 = F_4 = G_1 = G_4 = 1/\sqrt{2}\), \(D_2 = E_2 = F_2 = F_3 = G_2 = G_3 = i/\sqrt{2}\), we find

\[
\begin{align*}
    &P(f_1 & g_1) = \frac{1}{4}, \quad P(e_1 & f_2) = \frac{1}{8}, \quad P(e_1 & d_2) = \frac{1}{4}, \quad P(f_1 & g_2) = 0, \quad P(d_2 & f_2) = \frac{1}{8}, \quad P(e_2 & d_1) = \frac{1}{4}, \\
&\quad P(12) = 1.
\end{align*}
\]

In an actual experiment, we expect that pathlengths would need to be tuned carefully in order to obtain these effects. Rotating beamsplitter \(F\) so as to interchange the roles of reflection and transmission at \(F\) should then interchange the results for \(P(f_1 & g_1)\) and \(P(f_1 & g_2)\), confirming that constructive and destructive interference is taking place. Similar remarks apply to beamsplitter \(G\).

Proposed Experiment 3 should be viable with current technology. If interference effects were detected as predicted, then that would demonstrate not only that classical information extraction (at \(f_1\)) need not destroy interference taking place after that extraction, but also that such classical intervention can play an essential role in the optical paths involved.

Although it involves the possibility of self-intervening apparatus change, experiment 3 does not involve any erasure of such a change. To investigate this, we need to go further. To this end, we first return to the basic double-slit experiment and investigate what happens when we try to detect a photon at any of the slits.

V. EXPERIMENT 4: DOUBLE-SLIT WHICH-WAY DETECTION

The double-slit experiment with no which-path detection is shown in Figure 4.

The initial labstate is \(\Psi_0 = A_1a_1 + A_2a_2\), where \(|A_1|^2 + |A_2|^2 = 1\), and the detection screen consists of \(n\) ESDs \(\{s_i : i = 1, 2, \ldots, n\}\), with \(n \geq 2\). The dynamical rules for no-which-path detection are

\[
a_1 \to \sum_{i=1}^n S_i s_i, \quad a_2 \to \sum_{i=1}^n T_i s_i,
\]

where

\[
\sum_{i=1}^n |S_i|^2 = \sum_{i=1}^n |T_i|^2 = 1, \quad \sum_{i=1}^n S_i T_i^* = 0.
\]

Hence the final labstate is

\[
\Psi_1 = \sum_{i=1}^n (A_1 S_i + A_2 T_i) s_i,
\]

from which we read off the detection probabilities

\[
P(s_i) = |A_1 S_i + A_2 T_i|^2, \quad i = 1, 2, \ldots, n.
\]

These demonstrate quantum interference and sum to unity as required.

Now suppose that we allow for the possibility of detecting from which slit a photon came as it lands on the detecting screen. We introduce two new ESDs, labelled \(u\) and \(v\), which give information about \(a_1\) and \(a_2\) respectively. The experimental architecture is now given by Figure 5.

Assuming perfectly efficient detection at \(u\) and \(v\), the dynamics is now given by

\[
a_1 \to \sum_{i=1}^n S_i s_i u, \quad a_2 \to \sum_{i=1}^n T_i s_i v,
\]
so the final labstate is now

$$\Psi_2 = \sum_{i=1}^{n} \{A_1 S_i s_i u + A_2 T_i s_i v\}. \quad (18)$$

This time, we have the probabilities

$$P(u & s_i) = |A_1 S_i|^2, \quad P(v & s_i) = |A_2 T_i|^2, \quad (19)$$

which sum to unity. Moreover, the total probability $P(s_i)$ is just the sum $P(u & s_i) + P(v & s_i)$, which is the classical expectation showing no interference.

We can imagine performing a variant of this experiment where detection at each slit is not perfect, i.e., we consider a smooth transition from the complete which-path scheme of Figure 5 to the complete no-which-path scheme of Figure 4. We replace the dynamical schemes (13) or (17) by

$$a_1 \rightarrow \sum_{i=1}^{n} S_i \{\cos(\theta_1) + \sin(\theta_1)u\} s_i,$$
$$a_2 \rightarrow \sum_{i=1}^{n} T_i \{\cos(\theta_2) + \sin(\theta_2)v\} s_i, \quad (20)$$

where $\theta_1$ and $\theta_2$ are real. The case $\theta_1 = \theta_2 = 0$ corresponds to complete no-which-path information, Figure 4, whilst $\theta_1 = \theta_2 = \pi/2$ corresponds to complete which-path information, Figure 5. The final labstate is now given by

$$\Psi_1 = A_1 \sin(\theta_1) \sum_{i=1}^{n} S_i u s_i + A_2 \sin(\theta_2) \sum_{i=1}^{n} T_i v s_i$$
$$+ \sum_{i=1}^{n} \{A_1 S_i \cos(\theta_1) + A_2 T_i \cos(\theta_2)\} s_i \quad (21)$$

The respective probability distributions are readily read off and the total detection probability $P(s_i)$ at ESD $s_i$ turns out to be

$$P(s_i) = \{A_1 A_2^{-1} S_i T_i^* + A_1^* A_2 T_i S_i^*\} \cos(\theta_1) \cos(\theta_2)$$
$$+ |A_1 S_i|^2 + |A_2 T_i|^2. \quad (22)$$

This shows how the quantum interference term disappears the more which-path information becomes certain, i.e., in the limits when $\theta_1 \rightarrow \pi/2$ or $\theta_2 \rightarrow \pi/2$. A particular feature of the double-slit experiment is that detection at just one slit alone destroys the interference term. Another important feature is that elimination of which-way information is pre-determined by the observer choosing not to have any detection equipment at both slits, corresponding to $\theta_1 = \theta_2 = 0$, rather than any quantum erasure process of the type discussed in recent experiments [1]. What is surprising is that this choice is quite sufficient to produce interference on the detecting screen even in the case where the particles are bound states such as neutrons or molecules and cannot be regarded as elementary in any true sense.

Before the advent of quantum mechanics, any analysis suggesting that lack of which-path information about particle trajectories led to interference would have been regarded as fanciful. Yet double-slit interference is an experimental fact. It is reasonable, therefore, to investigate the possibility that such interference could happen on even larger macroscopic scales, provided true whichtway information was absent. To this end we propose the experiment discussed next.

VI. EXPERIMENT 5: INTERFERING BEAM Splitters

Consider the detector network shown in Figure 6, a modification of the double self-intervention network shown in Figure 2. The difference is that the triggered beamsplitters $F$ and $G$ now feed onto the same pair of ESDs labelled $f_1$ and $f_2$. Such an arrangement would require careful matching of the beamsplitters $F$ and $G$ beforehand.

The first two stages are as in Experiment 2, i.e., we have $\Psi_1 = (E_1 e_1 + E_2 e_2)(D_1 d_1 + D_2 d_2)$. We shall employ the same method as in Experiment 4 to parametrize the transition from complete no-which-path information to complete which-path information. We write

$$e_1 d_1 \rightarrow (\cos(\theta_1) + \sin(\theta_1)u)(F_1 f_1 + F_2 f_2),$$
$$e_1 d_2 \rightarrow e_1 d_2,$$
$$e_2 d_1 \rightarrow e_2 d_1,$$
$$e_2 d_2 \rightarrow (\cos(\theta_2) + \sin(\theta_2)v)(F_3 f_1 + F_4 f_2). \quad (23)$$

where the $\{F_i\}$ satisfy the unitarity relations discussed earlier. Hence we find

$$\Psi_2 = (E_1 D_1 F_1 \cos(\theta_1) + E_2 D_2 F_2 \cos(\theta_2)) f_1 + (E_1 D_1 F_2 \cos(\theta_1) + E_2 D_2 F_4 \cos(\theta_2)) f_2 + E_1 D_1 \sin(\theta_1)u(F_1 f_1 + F_2 f_2) + E_1 D_2 e_1 d_2$$
$$E_2 D_2 \sin(\theta_2)v(F_3 f_1 + F_4 f_2) + E_2 D_1 e_2 d_1, \quad (24)$$

FIG. 6: Proposed interfering beamsplitter experiment.
which gives the total probabilities $P(f_1), P(f_2)$ at ESDs $f_1$ and $f_2$ respectively to be

\[ P(f_1) = |E_1 D_1 F_1|^2 + |E_2 D_2 F_3|^2 + \begin{bmatrix} E_1 D_1 F_1 E_1^* D_2^* F_3^* + E_1^* D_1^* F_1^* E_2 D_2 F_3 \end{bmatrix} \cos(\theta_1) \cos(\theta_2), \]

\[ P(f_2) = |E_1 D_1 F_2|^2 + |E_2 D_2 F_4|^2 + \begin{bmatrix} E_1 D_1 F_2 E_3^* D_2^* F_4^* + E_1^* D_1^* F_2^* E_2 D_2 F_4 \end{bmatrix} \cos(\theta_1) \cos(\theta_2). \] (25)

In the limit where there is complete which-path detection, i.e., $\theta_1 = \pi/2$ or $\theta_2 = \pi/2$, we recover the results of Experiment 2, taking into account that $f_1$ and $f_2$ each then have to be regarded as two ESDs. In the limit of complete no-which-path information, i.e., $\theta_1 = \theta_2 = 0$, we expect to observe interference effects at $f_1$ and $f_2$.

The only real issue is whether all which-path information involving beam-splitters $F$ and $G$ could be eliminated by mechanical means sufficiently to produce interference. By this we mean removing all traces of which-beam splitter had been triggered, equivalent to an “information black hole”. This would undoubtedly require controlling the interaction between the triggering beamsplitters $F$ and $G$ and their environment, perhaps by intense cooling and shielding. The time scale for such erasure would undoubtedly be a critical factor also.

It is possible that no technology could be devised to erase all traces of beamsplitter switching, for both practical and theoretical reasons. Theoretically, resetting a triggered beamsplitter to its untriggered state amounts to resetting a pointer, and this is expected to carry a cost in terms of irreversibility. The discussion in [6] is relevant here.

If it really were the case that all information concerning the triggering of $F$ or $G$ could never be erased, then interference at $f_1$ and $f_2$ should never be observed, according to the rules of quantum mechanics. This would mean that there really were two types of erasure. The first can be called quantum erasure, examples of which are the double-slit experiment and the experiment discussed by Walborn et al. [1]. Interference can be observed in such cases. The second type of erasure, classical erasure, requires physical intervention on the part of the observer. The big question then is whether classical and quantum erasure are fundamentally different or not.

We believe that an experiment along the lines of our Experiment 5 could be viable with current technology, but it would not be easy. A sequence of steps would be taken, attempting to remove with more and more efficiency and completeness any trace of which-beam splitter had been triggered, corresponding to $\theta_1$ and $\theta_2$ both approaching 0. It is our intuition, based on the double-slit experiment and the experiment of Greenberger and YaSin [6], that a point should come where interference at $f_1$ and $f_2$ started to manifest itself, but where that point is and whether it is attainable in practice are open questions. Certainly, it would be an interesting experiment to attempt: even the slightest hint of interference at $f_1$ and $f_2$ would cast light on the fundamental questions “is there a Heisenberg cut?” and “if there is such a cut, where does it start?”.

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