Smoothly breaking unitarity : studying spontaneous collapse using two entangled, tuneable, coherent amplifiers

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Chapter 1

Introduction

1.1 Setting the stage: the measurement problem and the photodetector

Upon measurement a quantum system collapses onto one of the eigenstates of the measurement operator. The measurement outcome is then given by the eigenvalue corresponding to this eigenstate.
This is one of the postulates of the Copenhagen interpretation of quantum mechanics. It divides the world into two realms – the microscopic realm of quantum systems governed by quantum mechanics and the macroscopic realm of classical systems (measurement apparatuses) governed by classical mechanics.

Quantum mechanics and classical mechanics contain intrinsically different views of the world around us. Classical mechanics is deterministic: in principle, if we know the positions and momenta of all particles in the universe, we can – with certainty – determine the state of the universe at any other time by Newton's laws. Contrarily, from our classical point of view, quantum mechanics is probabilistic: a quantum system can only be described in terms of a quantum state, from which we can theoretically determine averages, standard deviations etc. of physical properties. Practically, we can only determine these variables using a large set of identically-prepared quantum systems, as "follows" from the measurement postulate stated above. Moreover, for a single system we cannot even measure all its properties as dictated by Heisenberg's uncertainty relation. Yet, within the realm of quantum mechanics, a quantum system is perfectly deterministic. Its time-evolution is described by Schrödinger's equation, implying that we can, in principle, determine the quantum state of the universe at any time, if only we had access to its quantum state at a certain time and the Hamiltonian of the universe.

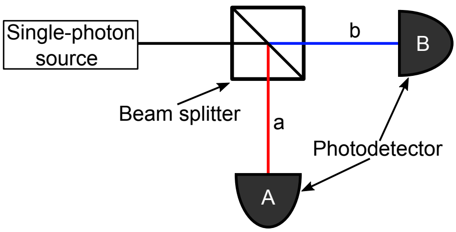

Figure 1.1: *Illustration of the quantum measurement problem. If a superposition of 0 and 1 photon is created using a single-photon source and a beam splitter, photodetectors A and B placed in the beam splitter's output arms a and b will either "click" or "not-click", whereas they should attain a superposition of clicking and not-clicking according to Schrödinger's equation that describes the unitary evolution of quantum states.*

Let us illustrate this by an example. Consider the set-up depicted in figure 1.1. A single photon, the archetype of a quantum system, is emitted by a single-photon source. The photon encounters a beam splitter, which "splits" the single photon into a superposition of 0 and 1 photon in each of the outputs of the beam splitter. In this case, the photon state after the beam splitter can be deterministically described by the state vector

$$|\psi\rangle = \alpha\,|1\rangle_{\mathrm{a}}\,|0\rangle_{\mathrm{b}} + \beta\,|0\rangle_{\mathrm{a}}\,|1\rangle_{\mathrm{b}}\,, \tag{1.1}$$

where $|\alpha|^2$ and $|\beta|^2$ are the probabilities of finding the corresponding states upon measurement.
If this state is absorbed by the photodetectors connected to the outputs of the beam splitter, one of the detectors "clicks" to indicate it has detected the photon. That is, once one of the detectors has clicked, the state can be described by

$$|\psi\rangle_{\mathrm{d}} = |1\rangle_{\mathrm{A}}\,|0\rangle_{\mathrm{B}} \vee |\psi\rangle_{\mathrm{d}} = |0\rangle_{\mathrm{A}}\,|1\rangle_{\mathrm{B}}\,. \tag{1.2}$$

Hence, only one of the detectors, A or B, clicks, which is in contradiction with the deterministic quantum evolution of the system that implies that the detectors should be in a superposition of clicking and not-clicking. The latter behaviour, however, is never observed in experiments and it is precisely this observation that leads to the formulation of the measurement postulate, which is also known as the measurement problem.

The mystery of state collapse has been a much-debated issue since the conceivement of quantum mechanics in the 1920s. Some of the view points on this issue will be presented in section 1.2. However, with the advancement of technology, we envision that the time has come to address this matter in an experimental setting. One may wonder whether it is really the measurement apparatus that induces state collapse. To this end we will consider undressing the photodetector to a quantum device, a parametric amplifier, in section 1.3. An overview of the remainder of this thesis is presented in section 1.4.

1.2 Interpretations of quantum state collapse

Ever since the formulation of quantum mechanics, interpretations of the theory have been put forward. These interpretations often include a view on the process of quantum state collapse. In this section we will shortly discuss the phenomenology of some common views, including remarks about problems raised by the interpretations. For an extended review and literature overview, see [1].

1.2.1 The Copenhagen interpretation

The first interpretation of quantum theory was developed in the years 1925 to 1927 in Copenhagen and is therefore known as the Copenhagen interpretation [2]. It says that a measurement apparatus collapses a quantum state irreducibly and probabilistically to an eigenstate of the observed quantity. Moreover, after

a measurement, a state can be described in classical terms.
Although the Copenhagen interpretation does not provide an explanation for state collapse, it does introduce the notion of a measurement apparatus (without defining what it is) and that there is a clear distinction between the quantum realm and the classical realm.

1.2.2 Bohmian Mechanics

As a solution to the measurement problem, Bohm proposed an extension of quantum mechanics by a guiding equation [3, 4]. This equation determines the real position and momentum of a corpuscle, which is guided by the quantum wave function and is the source of this wave at the same instance. Then, within the example given in previous section, when the single-photon quantum state encounters the beam splitter and splits, the corpuscle, which makes a detector click, is situated only in one of the branches of the superposition. This would explain why only one of the detectors clicks and the other does not-click. Moreover, one of the detectors will click deterministically as the path followed by the corpuscle only depends on its initial conditions.
This approach to quantum state collapse has its merits as it removes the uncertainty from the quantum measurement. As a matter of fact, experiments have been conducted that have been claimed to support this interpretation [5, 6]. However, we find three objections. First, the corpuscle cannot be related to the particle it describes, since it has no properties except for a position and velocity [7–9]. This makes the theory unfalsifiable as, in absence of any corpuscle properties, there is no means of verifying the existence of such a corpuscle. Furthermore, we doubt that such a corpuscle can exist, because to all known particles at least an energy can be associated. Thirdly, we note that this interpretation merely replaces the problem by a different problem, because in order to predict the measurement outcomes, the corpuscles must have the right initial conditions. This implies that the measurement problem is replaced one-to-one by the quantum source problem.

1.2.3 Many-worlds interpretation

The many-worlds interpretation of quantum mechanics is due to Everett [10]. This interpretation postulates that also during and after the process of measurement the unitary evolution described by the Schrödinger equation determines the evolution of a quantum state. However, after measurement, the measurement outcomes live in different orthogonal "branches" of the universe, such that they will never interact again. If a measurement can attain two experimental outcomes, such as a detector clicking or not-clicking, this can be seen as the single photon encountering a beam splitter: in the many world interpretation the beam splitter plays the role of a measurement and the two output channels of the beam splitter can be thought of as the different branches of the universe. This interpretation might have difficulties with falsification, if one considers the branching of universe as the fundamental aspect of the interpretation. Since the branches of the universe are orthogonal, we cannot detect the existence of a branched-off universe. That is to say, in analogy to the single photon and beam splitter, we cannot perform a measurement that acts as a second beam splitter which overlaps the two created universe branches again. However, this difficulty is erased if the unitary evolution described by Schrödinger's equation is considered as the core aspect of the theory. In that case the many-worlds interpretation would be falsified by either Bohmian mechanics (discussed above) or spontaneous collapse theories (discussed below), as these two interpretations require an extra ingredient to quantum evolution apart from the Schrödinger equation.

1.2.4 Environmental decoherence

Environmental decoherence describes the loss of quantum interference by interactions with the environment [11–13]. Consider the state matrix of the pure state described in equation (1.1) given by

$$\hat{\rho}_{\mathrm{p}} = |\psi\rangle \langle\psi| = \begin{bmatrix} |\alpha|^2 & \alpha\beta^* \\ \alpha^*\beta & |\beta|^2 \end{bmatrix}. \tag{1.3}$$

Due to coupling with the environment the off-diagonal terms in the state matrix exponentially tend to 0, leaving the mixed state $\hat{\rho}_{\mathrm{m}} = \mathrm{diag}(|\alpha|^2, |\beta|^2)$. Such processes have been observed in an experimental setting [14, 15].
The diagonal matrix $\hat{\rho}_{\mathrm{m}}$ is indistinguishable from a classical mixture and therefore it has been argued that it describes a collapsed state. However, strictly this is not the case: environmental decoherence only accounts for the destruction of quantum interference effects. It does not destroy the superposition of classical alternatives, as we will argue now.
Consider a set of marbles, let them be red and blue. If we draw a classical marble blindly (which is either red or blue) there is some probability of finding either colour. However, we know – since they are classical marbles – that the marble possessed that colour already before looking at it. However, in the case of quantum marbles, which are in a superposition of red and blue, the marble will decohere in our hand (the environment) before looking. Assuming the decoherence process lasts long enough to reduce the quantum marble's initial pure state $\hat{\rho}_{\mathrm{p}}$ to a final mixed state $\hat{\rho}_{\mathrm{m}}$, the state matrices of the classical and quantum marbles are the same before looking. However, although the classical and decohered state matrix are identical, for the quantum marble the colour is not necessarily determined before looking. In other words, although decoherence destroys the quantum mechanical interference phenomena of the system, it does not destroy the superposition of classical alternatives. This implies that environmental decoherence cannot account for the measurement problem.

1.2.5 Spontaneous collapse

As a last interpretation, we will discuss the idea of spontaneous collapse. Spontaneous collapse theories consider the option that the Schrödinger equation is incomplete and extend the evolution of a quantum state by a phenomenological collapse rate. The main idea is that every particle has an intrinsic collapse rate, which increases with particle mass. As such, the collapse rate of a single nucleon is small, such that it will behave according to the Schrödinger equation within the time frame of an experiment. Macroscopic particles, however, have such large collapse rates that the signatures of quantum mechanics are never observed in an experiment, because the quantum behaviour is too short-lived. In this view, the measurement problem can be thought of as a quantum system (with a small collapse rate) coupling to a measurement apparatus (with a large collapse rate). Thus the quantum system collapses due to the collapse rate that increases upon coupling.
The main disadvantage of this approach is that it is only phenomenological. There have been hypotheses developed as to what determines the collapse rate, mainly in the direction of trace dynamics [16] and gravity [17–19]. Proposals for the collapse rate (per nucleon) are orders of magnitude apart – the theory of Continuous Spontaneous Localisation (CSL) sets it at 10^{-17} Hz [20], whereas Adler estimates the collapse rate per nucleon at $10^{-8\pm2}$ Hz [21]. It is an area of active research to set bounds to the collapse rate [22–24].

1.3 Undressing the photodetector: the parametric amplifier

The interpretations presented in previous section are distinctly dissimilar in their view of quantum state collapse. However, they all agree that *large* systems appear to be classical, whereas microscopic systems behave quantum mechanically. From this notion an important question arises

What is large?

This question is currently approached by performing experiments on larger and larger physical systems to verify whether these systems behave according to quantum mechanics (see [25] for a review). At the moment of writing, systems of the size of small viruses have shown quantum mechanical behaviour [26] and an experiment testing the quantum behaviour of micrometre sized mirrors is being prepared [27].
Yet, in view of measurement apparatuses the question *What is large?* can be reformulated as

What is a measurement apparatus?

To illustrate, consider once more the experiment described in section 1.1. Now, suppose the photodetector is a photomultiplier tube (PMT), see figure 1.2. In PMTs an incoming photon causes a (primary) electron to emit from a cathode by the photoelectric effect. This electron is accelerated towards a dynode by an electric field. Due to the impact of the electron on the dynode, several (secondary) electrons are emitted. These, in turn, are accelerated towards a second dynode in which the process of electron multiplication is repeated. In the end, this results in a measurable current pulse of electrons arriving at the anode of the device.
Suppose now that a superposition of 0 and 1 photon, as described by equation (1.1) enters the PMT. Based on the postulate that measurements are responsible for quantum state collapse, one may wonder *where* during the amplification process within the PMT the state collapse happens, if it happens within the PMT at all. That is, at what point between the emission of the primary electron and the current pulse leaving the PMT the detector "decides" to click or not-click. Equivalently, one may wonder how many electrons are in superposition of remaining in and being emitted by a dynode when state collapse happens.

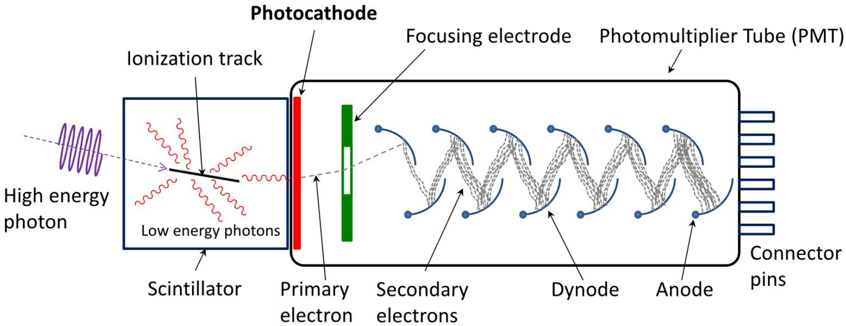

Figure 1.2: *Schematic overview of a photomultiplier tube (PMT). An incoming photon causes emission of an electron in the photocathode. This primary electron is accelerated by an electric field towards a dynode, where it causes the emission of several secondary electrons. This process is repeated to yield a measurable current pulse at the PMT's anode. A scintilator in front of the PMT may be used to decrease the effective energy of the incoming photon. Figure taken from [28].*

In this thesis we investigate an experiment addressing these questions. In principle, we could take the experimental set-up depicted in figure 1.1 and try to interfere the outputs of the two photodetectors. However, photodetectors are devices which are hard to describe within a quantum mechanical framework due to coupling to the environment and interfering their outputs is not at all trivial. However, the main characteristic of the photodetector – producing a click in the form of a detectable current by means of amplification when a photon enters

the device – can be mimicked by means of an electronic amplifier.
A certain class of electronic amplifiers, the so-called parametric amplifiers, is especially suited for this experiment. They produce gain due to non-linear wave mixing resulting from the variation of an amplifier parameter while the signal-to-be-amplified traverses the device. A parametric amplifier is tuneable in gain, can be quantum limited in noise figure and, most importantly, it can be described in quantum mechanical terms. Within an interferometer set-up we can interfere the outputs of two of such amplifiers which are entangled by feeding the interferometer with single photons. Building the whole set-up by use of superconducting devices, one can hope to achieve a sufficiently small coupling to the environment and add mass to the problem simultaneously. The latter occurs via the interaction of the electromagnetic waves transmitting through the set-up which are caused by the massive Cooper pairs in the superconducting transmission lines. By increasing the gain of the amplifiers, more and more Cooper pairs will partake in the quantum mechanical superposition, which can be seen as analogous to the increase in emitted electrons from the PMT dynodes.

1.4 Overview of the thesis

In this thesis we will take the first steps towards such an experiment. Chapter 2 presents a minimum background in microwave engineering as a basis for the rest of the thesis.
In chapter 3, a mesoscopic theory is developed that describes the process of non-linear wave mixing and the resulting gain in a transmission line embedded with Josephson junctions. Such a theory will be necessary to model the parametric amplifiers within a quantum mechanical framework correctly for the final experiment.
In chapter 4, we will present a prediction on the interference visibility that can be expected from an interferometer that has a parametric amplifier added to each of the interferometer arms. In this chapter we will also discuss the influence of losses in the interferometer on this visibility. This allows to estimate how small the coupling to the environment must be in order for the proposed experiment to work. Furthermore, we will argue how the interference visibility might change in case the quantum state collapses within the interferometer.
In the final chapter of this thesis, chapter 5, we present our findings on our attempts to develop a low-loss travelling-wave parametric amplifier. We present the design, fabrication procedure and findings from a transmitting device. The latter is used to validate the theory presented in chapter 3.

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