A Thought Experiment on ‘Passing on Quantum Superposition’

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June 2, 2022

Abstract

The concept of a wave function collapse forms an important part of the traditional Copenhagen interpretation of quantum theory. A wave function collapse can be said to take place at a measurement device when it performs an observation on a quantum system. This collapse of the wave function forms the beginning of our classical world. As, in principle, quantum mechanics applies the same to larger systems, a second possibility can be thought up. The measurement device, instead of a single classical state, could go into a state of superposition. A thought experiment is proposed to probe the question of whether a quantum system that is in a state of superposition could pass on its superposition to a measurement device. That is, to see if a measurement device could ever be in a state of superposition. This thought experiment shows two different outcomes based on what occurs at the measurement device. A few intricacies of a measurement device being in superposition, if it can even be, are brought up at the end.

1 Introduction

In quantum theory, a wave function evolves continuously when left to itself. However, on observation, it undergoes an instantaneous ‘wave function collapse’. This constitutes the traditional Copenhagen interpretation[1]. And it is not explicitly specified how an observation and a unitary interaction differ.

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from each other. Many have proposed different interpretations of quantum mechanics, some even without the idea of a wave function collapse. But as most of the interpretations share the same experimental outcomes, it is hard to prove any of them.

Fortunately, the mathematics that is followed by a quantum system has never been known to fail and has been applied to increasingly larger systems. Many phenomena widely different from our classical world have been seen. It is also not properly known where applicability of the quantum theory stops and the classical world begins to take over. As von Neumann writes, the mathematics of quantum theory allows a wave function collapse to be placed at any position in a causal chain of measurement devices up to the ‘subjective perception’ of a human observer[2]. The point where we place the collapse of the wave function can be said to be the point where the classical world starts.

This article proposes a thought experiment addressing a part of von Neumann’s statement. Specifically, the question of whether a quantum system that is in superposition could pass on its state of superposition to a measurement device (to form a causal chain).

2 A Measurement Process

Choose a beam of circularly polarized light in the state-

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|R\rangle + |L\rangle)$$  \hspace{1cm} (1)

$|R\rangle$ and $|L\rangle$ indicate right and left circularly polarized light, respectively. When the beam of light passes through a Fresnel polyprism[3], it splits into right and left circularly polarized beams, respectively. This is an analogue of the Stern-Gerlach experiment with silver atoms. Two single-photon detectors[4] at the two beams constitute a ‘measurement device’. See Ref [4] for more on single-photon detectors. See Figure 1.

The state of the whole system evolves into-

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|R\rangle|D_1\rangle + |L\rangle|D_2\rangle)$$  \hspace{1cm} (2)

$|D_1\rangle$ and $|D_2\rangle$ indicate the detection of a photon at detectors $D_1$ and $D_2$, respectively. Since detecting a photon at $D_1$ or $D_2$ shows, with certainty,
Figure 1: A beam of light splits into right and left circularly polarized light, respectively and are detected at detectors $D_1$ and $D_2$

the state of polarization of the photon, a wave function collapse occurs at the ‘measurement device’. As wave function collapse makes the system lose its quantum property of a superposed state, it forms the beginning of our everyday classical world.

If we, on the other hand, treat the ‘measurement device’ as a quantum system as well, a second possibility of the ‘measurement device’ being in superposition arises. A wave function collapse might not occur. Instead, the two detectors forming the ‘measurement device’ might go into a state of superposition.

3 Hong-Ou-Mandel Effect

To probe this question, we shall make use of a two-photon quantum interference effect known as the ‘Hong-Ou-Mandel Effect’ [5]. The following section gives a simple account of how the effect works.

Consider a non-linear crystal that splits a photon into two of equal wavelength by a down conversion process. These photons are further reflected from two mirrors, $M_1$ and $M_2$, and encounter a beam splitter. They, then, undergo a coincidence detection by two detectors, $D_A$ and $D_B$. In coincidence detection, a detection is counted only if a photon is detected at the same time at both the detectors $D_A$ and $D_B$ each. If two photons are detected at one detector while none at the other, then the event is not counted. See Figure 2.

Considering Figure 2, the photons that are detected at $D_A$ and $D_B$ can come from either mirror $M_1$ or $M_2$. And on reflection, a photon experiences a phase shift of $\pi/2$. Thus, there can be four possible outcomes for the state
Figure 2: Hong-Ou-Mandel Effect- A non-linear crystal splits a photon into two of equal wavelength and they are detected at $D_A$ and $D_B$ by coincidence detection of the detectors $D_A$ and $D_B$. The total state can be written as-

$$|\phi\rangle = \frac{1}{2} \left( |A_1B_1\rangle + e^{i\pi/2} |A_2B_0\rangle + e^{i\pi/2} |A_0B_2\rangle + e^{i\pi} |A_1B_1\rangle \right) \quad (3)$$

The subscript denotes the number of detections. Since the photons are of equal wavelength and indistinguishable, the first and last term of the above equation can cancel each other. Thus,

$$|\phi\rangle = \frac{e^{i\pi/2}}{2} (|A_2B_0\rangle + |A_0B_2\rangle) \quad (4)$$

From the above equation, we can see that there is no possibility of a photon being detected by the two detectors $D_A$ and $D_B$ each and we can conclude that a coincidence count would give zero coincidences. The two photons would always come out together, either at one detector or the other. This zero coincidence detection effectively gives us a method to see if two photons are indistinguishable or not without actually measuring their states. See Ref [5] for more.

If the two photons, on the other hand, are not indistinguishable, the two terms can no longer cancel each other, and all four of the outcomes can occur. From Eq (3), it can be concluded that half of the total detection events would be coincidence counts.

4 The Thought Experiment

Let’s proceed with the thought experiment. A measurement process was described in the earlier section. It expressed the state of the whole system
after encountering the detectors as $|\psi\rangle = \frac{1}{\sqrt{2}}(|R\rangle|D_1\rangle + |L\rangle|D_2\rangle)$.

Couple the two single-photon detectors $D_1$ and $D_2$ from before with two single-photon emitters $E_1$ and $E_2$. Ref [4] contains a review of single-photon detectors and single-photon emitters. On a trigger pulse from a single-photon detector, its coupled single-photon emitter emits a photon. Let the photons emitted by emitters $E_1$ and $E_2$ be horizontally and vertically polarized, respectively. The state of the system evolves now into

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|R\rangle|D_1\rangle|H\rangle + |L\rangle|D_2\rangle|V\rangle) \quad (5)$$

Now, the two photon paths are merged into one by a birefringent crystal. A second identical apparatus of the whole experiment gives one more photon. These two photons come upon a Hong-Ou-Mandel Interferometer. See Figure 3.

Figure 3: Two photons from two identical ‘measurement devices’ that measured the same initial state $\psi$ form the input photons to a Hong-Ou-Mandel Interferometer. A zero coincidence count would show the ‘measurement device’ to be in superposition.

On doing a coincidence detection at the detectors $D_A$ and $D_B$, there can be two possible outcomes. Zero coincidences and non-zero coincidences. A zero coincidence count would show that the two input photons are indistinguishable from each other. If they are indistinguishable, then they must be in a state of superposition as they are photons from two ‘measurement devices’. A wave function collapse must not have occurred at the ‘measurement
device’. Further, it would show that superposition has indeed passed on to the ‘measurement device’.

On the other hand, a non-zero coincidence count would indicate that a wave function collapse must have occurred at the ‘measurement device’. Consider Eq (5) which is $|\psi\rangle = \frac{1}{\sqrt{2}}(|R\rangle |D_1\rangle |H\rangle + |L\rangle |D_2\rangle |V\rangle)$. A photon coming out of the birefringent crystal has an equal probability of being horizontally or vertically polarized. Thus, there can be four possibilities of polarization for the two photons going into the Hong-Ou-Mandel Interferometer. Their state can be written as-

$$|\psi_1\psi_2\rangle = \frac{1}{2}(|H_1 H_2\rangle + |H_1 V_2\rangle + |V_1 H_2\rangle + |V_1 V_2\rangle) \quad (6)$$

The subscripts 1 and 2 indicate the photons from the first and second ‘measurement devices’, respectively. If the two photons have identical polarization, they have zero coincidence count due to their indistinguishability. If the two photons have different polarization, they have half of the total detection events as coincidence counts. The total coincidence probability can be calculated as-

$$\frac{0 + 0.5 + 0.5 + 0}{1 + 1 + 1 + 1} = \frac{1}{4} \quad (7)$$

Thus, a quarter of the total detection events would be coincidence counts if we consider a wave function collapse has occurred at the ‘measurement device’.

5 Discussion

The thought experiment shows two different outcomes based on whether there is a wave function collapse at the ‘measurement device’ or not. There is an important point to note. The ‘measurement device’, if it can exist in superposition, must have a ‘fragile’ superposed state as any exposure of its state to the classical macroscopic world seems enough to break it.

To maintain superposition, if it exists, it remains important that the measurement process is destructive and the ‘measurement device’ is closed and exhibits absolutely no distinguishability during the entire duration of the experiment and even after that with no record of anything that happened inside the ‘measurement device’.

Realizing this phenomenon of superposition being passed on to a measurement device may deepen our understanding of the quantum world and
increase our knowledge on how the quantum world gradually transforms to a classical world. It may prove a part of von Neumann’s statement and thus increase the applicability of quantum theory to macro objects.

This work has benefited substantially through discussions with Prof. Urjit Yajnik, IIT-Bombay, India.

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