An Experimental Proposal for Demonstration of Macroscopic Quantum Effects

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An experiment is proposed, whose purpose is to determine whether quantum indeterminism can be observed on a truly macroscopic scale. The experiment involves using a double-slit plate or interferometer and a macroscopic mechanical switch. The objective is to determine whether or not the switch can take on an indeterminate state.

1 Introduction

Since the founding of quantum theory in the last century, there has been the question of what limit, if any, there is to the quantum effects which may be observed, in terms of size or number of particles of a system under observation. By *quantum effects*, it is meant in particular, phenomena such as entanglement or indeterminism. The most famous gedankenexperiment in quantum theory, *Schrödingers cat*, concerns this *macroscopic* question. This *cat paradox* argument was used by Schrödinger to ridicule the Copenhagen interpretation of quantum theory. [1]. Another well-known paradox was that of Einstein, Podolsky and Rosen [2] commonly referred to as the *EPR paradox*. This gedankenexperiment was also an attempt to discredit the Copenhagen interpretation, but for a different reason than that of the cat paradox.

Regrettably, there are few known experiments that demonstrate whither the macroscopic question, unlike with the EPR paradox. A recent experiment [3] has shown that quantum effects *i.e.* entanglement, can occur between systems of $O(10^{12})$ particles. Although these results are encouraging, such a system can hardly be termed macroscopic in spite of the title of the article in which it appears. Here, we consider a *macroscopic* system to be one clearly visible to the naked eye and in the solid state, such as Schrödingers cat. Another experiment, of Schmidt [4], seems to demonstrate that bits on a computer disk, even printouts of ones and zeros concealed in an envelope, take on indeterminate states. However, the desire remains for further proof of macroscopic quantum effects, in particular, absent of paranormal phenomena and resulting complications [5]. Perhaps the reason that evidence of macroscopic quantum effects is so few and far between is because macroscopic analogs to experiments such as the double-slit experiment are difficult to design. One cannot simply shoot cats through a double slit and expect to see an interference pattern!

Instead of shooting Schrödingers cat through the double slit, suppose the cat is kept in its box, but a large double slit plate is also placed inside the box. Things are arranged so that the cat in the alive state obstructs one slit, and the cat in the dead state obstructs the other. All in the box is concealed from the observer and also, many cats would need to be used. See Figure 1. Now the question arises: will an interference pattern be observed on the screen if individual photons are transmitted through the double slit and box, one by one? If interference is observed, would this indicate that the cats were in an alive-dead state? The answer is in the affirmative; for if the cats were each definitely either alive or dead when the photons passed through, then no interference pattern should be observed.

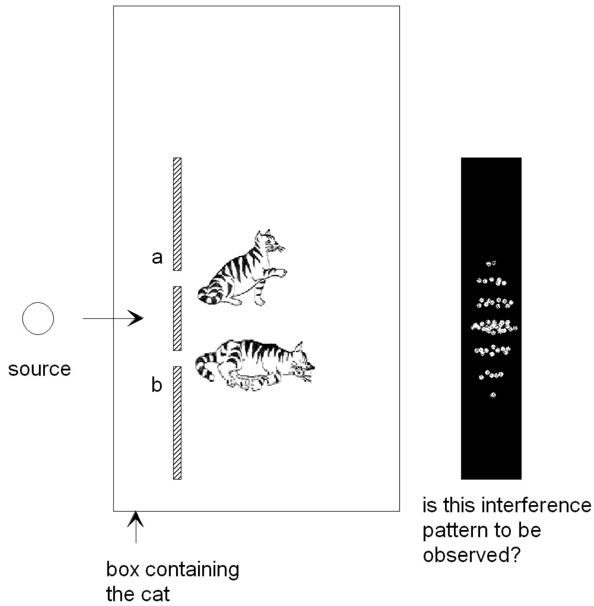

Fig. 1: An experiment with Schrödingers cat and a double slit. The experiment is designed so that if the cat is in the alive state, it obstructs slit **a** and if the cat is in the dead state it obstructs slit **b**. Many cats are needed for the experiment. If the cats remain unobserved and individual photons are transmitted through the double-slit and box, the question is: would an interference pattern be observed on the screen, and further, does this signify that the cats were in a superposition of alive and dead states?

In the next section, a more realizable (and cat-friendly) experimental set-up than the previous is proposed. This experiment will aid in answering the question of macroscopic indeterminism, as the accompanying calculations show. Although the set-up is quite simple by todays standards, it is not the intention of the author, a theorist, to carry out the experiment. Rather, it is hoped that an experimentalist is willing to carry out the necessary work.

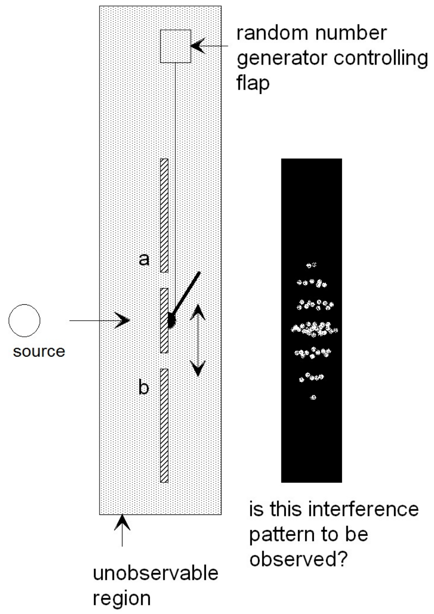

Fig. 2: The apparatus in Figure 1 is now modified so that a flap takes the place of Schrödingers cat. The flap position is controlled by an indeterministic random number generator, in order to put the flap in an indeterminate state with regard to which slit it covers. If measures are taken to destroy information about the flaps position before the photons reach the screen, the individual photons passing through the double slit apparatus should build up an interference pattern on the screen.

2 Double-slit experiment

Consider a set-up with a double slit, as in Figure 2. The difference between this set-up and the previous is that a flap takes the place of the cat. The flap covers either one slit or the other, and alternates between the two positions, controlled by a random-number generator.

The random number generator, flap and double-slit are concealed from the observer. The random number generator should be of the indeterministic type such as the one developed by Stipčević and Rogina [6]. The purpose of this is to put the flap into an indeterminate state. The set-up in Figure 2 is similar to one proposed by Mandel [7] which was carried out by Sillitto and Wykes [8]. However in that experiment, photons were *not* transmitted individually. So it is likely that the experiment was *not* free of photon-photon interference, whereas in the experiment under consideration here, such interference must be eliminated. Also, it is unclear if the electro-optic shutter used in that experiment could be said to be in an indeterminate state or to even be a mechanical macroscopic object.

Assuming that the flap in Figure 2 can be put into an indeterminate state, the flap can be represented by the equation

$$|\psi\rangle = \frac{1}{\sqrt{2}}\Big(|\mathbf{a}_f\rangle + |\mathbf{b}_f\rangle\Big), \tag{1}$$

where $|\mathbf{a}_f\rangle$, $|\mathbf{b}_f\rangle$ are the basis states representing the flap f covering slits **a** and **b**, respectively. Now if a single photon p passes through the double-slit, say it passes through slit **b**, then the flap must be covering slit **a**, and *vice versa*. Thus, each photon passing through the double-slit is entangled together with the flap, and the flap-photon entangled state is:

$$|\psi\rangle = \frac{1}{\sqrt{2}}\Big(|\mathbf{a}_f\rangle|\mathbf{b}_p\rangle + |\mathbf{b}_f\rangle|\mathbf{a}_p\rangle\Big), \tag{2}$$

where $|\mathbf{a}_p\rangle$, $|\mathbf{b}_p\rangle$ are the basis states for photon p. Equation (2) indicates that each photon passing through the double-slit takes on an indeterminate state with regards to which slit it passes through. Individual photons in the state (2) will build up an interference pattern if certain precautions are taken. Rather than using equation (2) to calculate the pattern which results from the set-up in Figure 2, we look at a variation of this experiment, for which it is easier to calculate interference. The apparatus is shown in Figure 3, in the next section.

3 Mach-Zehnder interferometer experiment

The set-up in Figure 3 essentially involves the same experiment as that shown in Figure 2, except that the isolated photons traverse a Mach-Zehnder interferometer (MZ) instead of a double-slit, and a moveable mirror (rm) replaces the flap. The rotation of the mirror rm switches the photon trajectory between two possible paths through MZ. The two different configurations are shown in the figure, top and bottom. Similar to the previous experiment, rm is to be put into an indeterminate state by controlling it with an indeterministic random number generator concealed from the observer (not shown in figure), and isolated photons can only be allowed to enter MZ through a gate. Further, position information of rm must be destroyed before each time a photon reaches the detectors. After such precautions are taken, the photons should each take an indeterminate path through MZ. Interference patterns of photon counts *vs.* relative length or phase between paths, the same observed by Aspect, Grangier and Roger [9] will then be seen. We next calculate these interference patterns.

Suppose first, rm is in the down position (upper diagram in Figure 3). This causes the photon to take the lower (–) path through MZ. Conversely, if the mirror is in the up position (lower diagram in Figure 3), the photon will take the upper (+) path through MZ. If rm can be prepared in an indeterminate state between up and down positions, then what results is the following entangled state between photon and mirror [*cf.* equation (2)]:

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|\text{rm up}\rangle|+\rangle + |\text{rm down}\rangle|-\rangle\right), \tag{3}$$

where $|\text{rm up}\rangle$, $|\text{rm down}\rangle$ are the two possible basis states for the moveable mirror rm and $|+\rangle$, $|-\rangle$ are the resultant basis states of the photon traversing MZ.

Let ϕ be the phase shift between arms of MZ, due to the presence of a phase shifter, or to a variation in the arms relative lengths. Using the rotation transformation equations

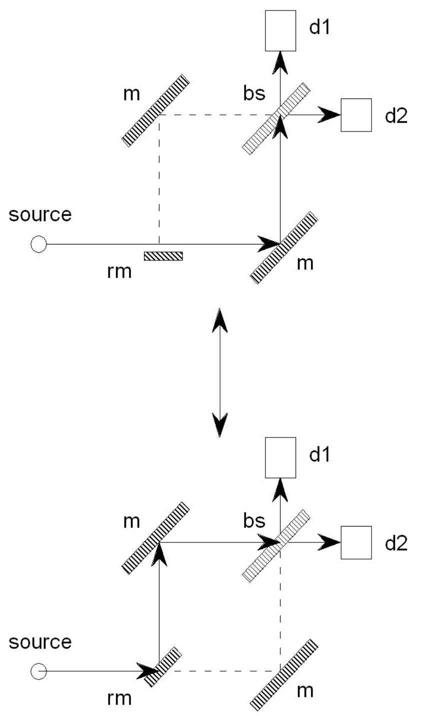

Fig. 3: A Mach-Zehnder (MZ) interferometer instead of the double slit of Figure 2. The moveable mirror rm acts as the former flap. The devices labeled m are fixed mirrors, bs, a beam splitter and d1, d2 are detectors. When rm is in the horizontal (down) position as at top, the photon takes the lower (–) path of mz (solid line with arrows). When rm is in the 45-degree position (up) as at bottom, then the photon takes the upper (+) path. If rm can take on an indeterminate state between these two configurations, then the photon paths will also be indeterminate, and thus interference patterns will result in d1 and d2, as variations of photon counts *vs.* relative length or phase ϕ between the two paths.

$|+\rangle = \sin\phi|d1\rangle + \cos\phi|d2\rangle$, $|-\rangle = \cos\phi|d1\rangle - \sin\phi|d2\rangle$ to put state (3) into the basis $|d1\rangle$, $|d2\rangle$ of the detectors, we obtain:

$$|\psi\rangle = \frac{1}{\sqrt{2}}\Big(\sin\phi|\text{rm up}\rangle|d1\rangle + \cos\phi|\text{rm up}\rangle|d2\rangle + \\ + \cos\phi|\text{rm down}\rangle|d1\rangle - \sin\phi|\text{rm down}\rangle|d2\rangle\Big). \tag{4}$$

If rm is successfully put into an indeterminate state, then the detector probabilities will be, using equation (4):

$$p\,(\text{d1}) = |<\text{rm up, d1}|\psi\rangle + <\text{rm down, d1}|\psi\rangle|^2 = \\ = \frac{1}{2}\,(1+\sin 2\phi) \tag{5}$$

and

$$p(\text{d2}) = \frac{1}{2}\,(1-\sin 2\phi)\,. \tag{6}$$

That is, interference fringes will be observed as oppositely-modulated signal intensity ($\propto$ probability) as a function of relative phase ϕ. These interference patterns; *i.e.* the interference patterns predicted by equations (5) and (6) are the same observed by Aspect and co-workers [9] using a similar set-up.

On the other hand, if rm remains in a *determinate* state, then *no* interference fringes will be observed; *i.e.* the signal intensity *vs.* phase-shift ϕ will be flat:

$$p\,(\text{d1}) = |<\text{rm up, d1}|\psi\rangle|^2 + |<\text{rm down, d1}|\psi\rangle|^2 = \frac{1}{2} \tag{7}$$

and

$$p\,(\text{d2}) = \frac{1}{2}\,. \tag{8}$$

Thus we have that: *the interference patterns* (5), (6) *result if and only if rm is in an indeterminate state. Presence of the interference patterns* (5), (6) *is therefore proof of macroscopic indeterminism, since the moveable mirror rm is a macroscopic object.*

It is emphasized again that it is important for the experimenter to take care that any information about the position of moveable mirror rm during the experiment is destroyed. This means that the random number generator should reset rm after each time an individual photon exits MZ, prior to the photon reaching detectors d1 or d2; otherwise in principle at least, the experimenter could discover which path the photon passed through, by uncovering rm. In that case, *no* interference [*i.e.* equations (7) and (8)] will be observed. Additional time to allow resetting rm can be obtained by placing d1 and d2 at some distance beyond the half-silvered mirror bs.

The experimental set-up of Figure 3 is similar to one proposed by Žukowski *et al.* [10], except that they propose to use a pair of electro-optical switches (one for each arm of MZ), instead of a moveable mirror before the arms. This is because the object of their proposal is to demonstrate whether or not the individual photons traverse MZ using both paths when the photon wave packet is cut in two using the switches as it passes though MZ. Their aim is to determine which of several interpretations of quantum theory is correct [11]. The purpose of that experiment is *not* to determine if the electro-optical switches take on an indeterminate state, even if again, such switches could be called mechanical and macroscopic.

4 Conclusion

An experiment involving individual photons passing through a double-slit plate or Mach-Zehnder interferometer apparatus has been proposed. Rather than keep both paths in the plate or apparatus open at all times however, one path or the other is kept closed by a macroscopic mechanical switch, controlled by an indeterministic device. The purpose of this is to determine whether the macroscopic switch can take on an indeterminate state: such indeterminism is detectible, dependent on whether an interference pattern results.

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