Quantum Theory and Some Confounding Experiments

I want you to imagine a world. One where objects have no defined position, and instead appear as clouds of probability. In this world, I may know that my cat Gruffydd is in my house, but I don't know in which room – in fact, he is in all of them, and none of them, until I open the door and find him in the hall. In this world, I know my friend Llew cycles to Cardiff every day. However, as soon as I try to find out the exact route he takes, he ends up in Swansea! You might conclude that something seriously fishy is going on in this bizarre world and might choose to remain instead in our much more straightforward world. Yet, as we zoom in closer and closer on our trusty logical world, entering the realm of atoms, electrons and photons, we are greeted with a 'microworld' akin to the world I first described. Here, particles behave differently depending on what we know about them, and display both the characteristics of a wave and a particle, depending on which experiments we use. This is the quantum world, the one that underpins our very own macroworld, and I want to show you a glimpse of it.

A first key idea is "superposition", where an object's state can be a mixture of several distinct states. Let's use an example – suppose we have a coin. If I flip this coin and quickly cover it with my hand, we wouldn't know which way up it's landed. However, we can agree that us observing the coin does not affect the result – underneath my hand, it is definitely either heads or tails. I reveal it; it's heads. Now let's imagine using a quantum mechanical coin. Again, I flip it and cover it with my hand. We don't know which way it's landed, and, while it's hidden under my hand, it is actually now in a superposition state – a mixture of both heads and tails. It is only once I reveal it that this superposition state "collapses" into either a 'heads' state or a 'tails' state. I reveal it; it's tails. Remember, the real coin always had a definite state of either heads or tails. On the other hand, the quantum coin was in a superposition state *until* the moment I revealed it, at which point the superposition state collapsed into a single definite state and became just like the real coin. In a real-life example, particles are in fact clouds of probability until we measure their position, at which their superposition state collapses into one of its many possible definite positions. While hard to wrap your head around, this superposition of states is one of the fundamental aspects of quantum theory.

An experiment that demonstrates superposition, as well as some of the other peculiarities, is Thomas Young's famous double-slit experiment in 1801. The setup involves a metal plate with two slits in it, and a receiving screen behind it. Young fired photons (light) at the screen and we'll be using electrons, but let's first imagine what would happen in the macroworld. If we had a machine gun firing at the setup, each bullet would either hit the metal plate or go through one of the slits. At the end, we'll have two rectangles of bullet holes corresponding to the two slits. If instead we submerged the slits in a pool and sent a ripple of water through the slits, we would see the phenomenon of diffraction at both of the slits and the two resulting ripples would interfere with each other (Figure 1), producing an interference pattern on the receiving screen (see Figure 2). So, we can see the two different results that would occur if we fired bullets (particles) or sent water ripples (waves) through the two slits.

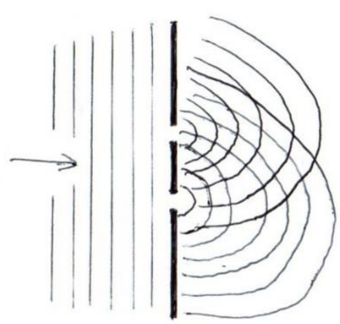

Figure 1 *A drawing of diffraction at two slits in a barrier.*

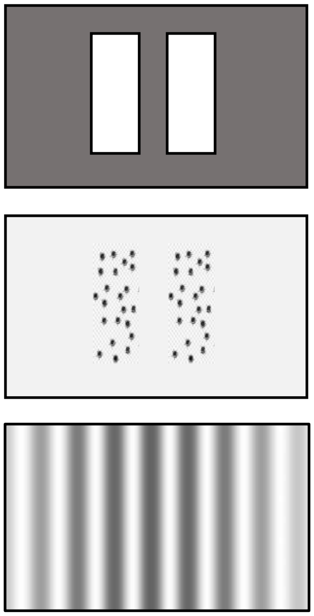

Figure 2 *Top, metal sheet with two slits used in Young's experiment. Middle, result on screen if bullets fired at slits. Bottom, result on screen if waves fired at slits.*

Now, let's go to the quantum world. Here we use an electron gun to fire electrons, which are fundamental particle. We expect some of the electrons to hit the metal plate and some to go through one of the slits, ultimately resulting in two rectangles of dots, like with bullets. However, as more and more electrons land on the receiving screen, we see something unusual – instead of two rectangles of dots, we see an interference pattern as if we had sent a wave through! We know the electrons are coming through as single particles because we saw them hit the screen as single dots, but, over time, these dots come together to form an interference pattern (Figure 3). The next question is "What on earth is happening at the slits?" So, we place a 'camera' of sorts to see which slit each electron is going through and rerun the experiment with a new receiving screen. The dots build up, but no interference pattern! Instead, the electrons act purely as particles and we see two rectangles of dots, just as we would if we had used bullets. Remove the camera, and the interference pattern returns.

So, what are we witnessing? Well, firstly we're seeing another important part of the quantum world – wave-particle duality: that particles can display both the characteristics of a wave and a particle. In our macroworld, it's nonsensical to talk of a football acting like a wave. But it turns out, rather unsettlingly, that objects at a small enough scale can show the characteristics of both. Secondly, we're seeing the effects of superposition first-hand! Before we added a camera, we had no way of knowing which of the slits each electron had gone through - we were lacking "pathway information". Because of this lack of information, there were two equally possible paths the electron could have taken – two possible states. As a result, until we have found out which path the electron took, it is in fact in a superposition state of the two paths. Put simply, it is then the two possible states that the electron could have occupied which interfere with each other to create the interference pattern witnessed - pretty abstract for a result we can easily see. Finally, the third thing we witness is superposition collapse. By placing a camera at one of the slits, we gain that pathway information we previously lacked, and the electron's superposition state collapses into a definite path of either the left or right slit. As a result, there are no longer two possible states to interfere with one another, and we are left with a much more classical view of bullets being fired through holes. This is truly an amazing experiment that shows us some peculiar consequences of the quantum world, clear as day.

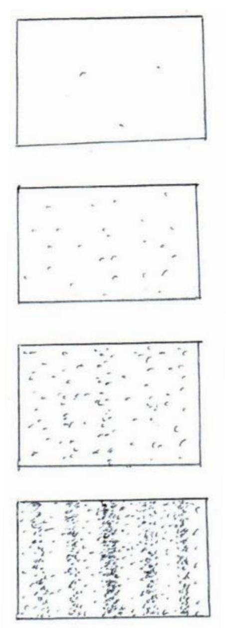

Figure 3 *A drawing of the accumulation of electrons on the receiving screen over time. Single dots build up to create an interference pattern.*

Another fantastic experiment is one that exhibits "interaction-free measurement". Normally, to detect anything, we need something to be reflected back off it, like light. However, the next experiment shows this is not the case. We start with the setup of a so-called Mach-Zehnder interferometer. As shown here, it involves a photon gun firing at a 50:50 splitter. This is simply a sheet of glass that has a 50% chance of reflecting the photon, making it take the anticlockwise route, and a 50% chance of transmitting it, letting the photon pass through and take the clockwise route. After this, the photon encounters another beam splitter. The same 50:50 chance of transmission or reflection occurs, and then the photon is received by either detectors D_1 or D_2 as a "click".

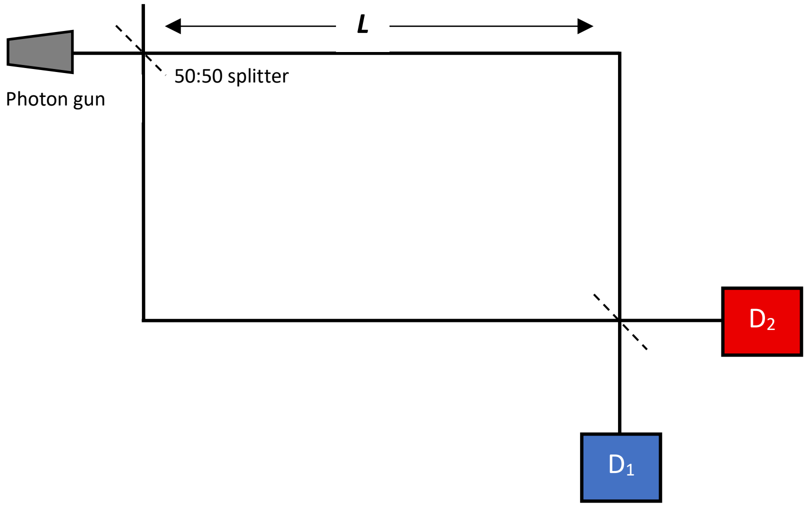

Figure 4 *A Mach-Zehnder interferometer setup. A photon is sent through two 50:50 splitters before being received by one of two detectors. The splitters hide any pathway information, resulting in a superposition state.*

The crucial part here is that the two 50:50 splitters stop us knowing which path the photon took. Due to the lack of any pathway information, the photon now is in a superposition state regarding the path it took, much like our experiment with the double-slit. When the electron was in a superposition state, we witnessed wavelike characteristics. So where are the waves here?

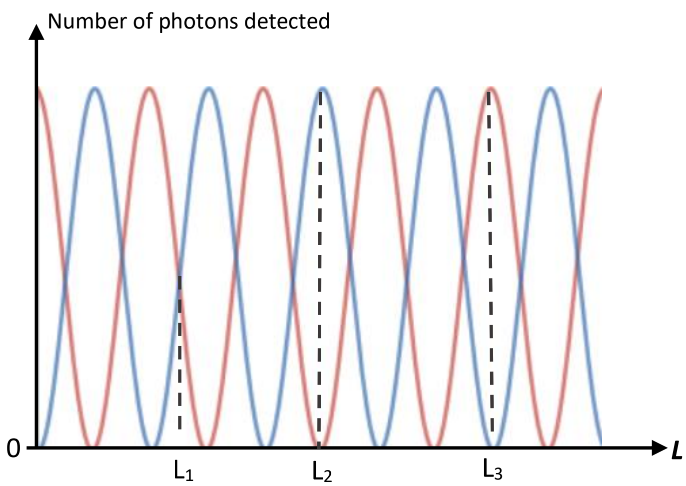

Figure 5 *A graph plotting length* ***L*** *against number of photons detected at each detector, where D_1 is blue and D_2 is red. By altering* ***L*** *to different lengths, we can choose what percentage of clicks each detector reports.*

It turns out that if we adjust ***L***, the length of one of the sides, we witness waves. Figure 5 shows the number of photons detected at each detector. The number goes up and down smoothly depending on the length of ***L***. At certain lengths, such as L_1, the detectors behave as we would expect, with each one detecting 50% of the photons. But at L_2, D_1 detects all the photons – absolutely no photons end up in D_2. Conversely, at L_3, all the photons are received by D_2. This is already quite bizarre; we can change the proportion of clicks between the detectors from 50-50 to 100-0 simply by changing the length of one side of the setup.

It gets spookier! Let's change ***L*** to L_2, so D_1 is receiving 100% of the photons and D_2 is not clicking at all. Now, we place an object in one of the paths, as shown in Figure 6. By blocking this path, we now know that any photons we detect must have taken the clockwise path – otherwise they would've hit the object. Suddenly, we gain pathway information. The superposition state collapses, and we get the two detectors reporting completely equal clicks, as if the photons were simple particles.

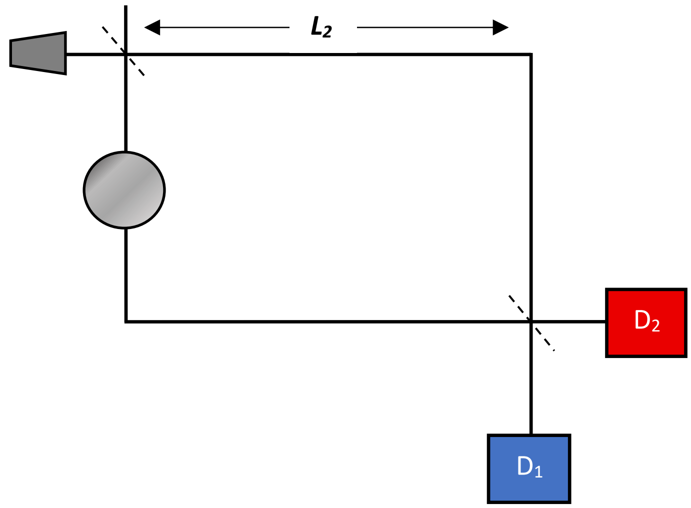

Figure 6 *By placing an object in the way of one of the paths, we gain pathway information. Photons will still be split 50:50 at the first beam splitter, but we know that any photons we receive at the detectors must have taken the clockwise path.*

This makes sense – pathway information collapses superposition states and gets rid of interference patterns. The amazing part is that these photons, that haven't interacted in anyway with this object, have told us about its presence. This is interaction-free measurement, and it is quite astounding.

There are many more mind-boggling results to wrap your head around in quantum experimentation, but I feel these two experiments are a good starter. If you feel this is all absurd, then you're not alone - many leading scientists were deeply uncomfortable with the idea of superposition and its implications. One significant contributor to the theory, Erwin Schrödinger, said, "I don't like it, and I'm sorry I had anything to do with it". He in fact envisaged a very famous thought experiment to highlight the absurdity of it – imagine a cat inside a box, with a device that releases poison relying on an atom's 50-50 chance of decaying over an hour. So, after an hour, the atom is in a superposition state of either having decayed or not. Is it also the case that the poison device is in a superposition state between being released and not released? And the cat is in a superposition state of being dead or alive? It doesn't quite make sense – at what scale does the world stop working with superposition states and start acting like ours? Luckily, we can keep our cats live and healthy and still investigate this. To this day scientists are still struggling to reconcile quantum theory with our macroworld and answer many of these questions. Whether or not you want to get involved in the search for truth, I hope you now have some things to mull over as you look around at our wonderfully complex world.