

## 12 Wavefunction Collapse

We have mentioned a number of times that a system can be in a state in which it does not possess a well defined value of a quantity that we would normally expect a classical system to possess - such a exact position, and exact momentum, or in the case of particles with spin, a well-defined component of spin in *any* given direction. We have also pointed out that when a measurement of a given quantity is made, the state of the system is converted into one in which a given quantity is indeed well-defined. What happens to the wavefunction describing the system when that happens is called “wavefunction collapse” and was first proposed by Heisenberg [24]. Wavefunction collapse takes a system from being a superposition of states, such as a superposition of a spin up state and spin down state to a wavefunction which either describes spin up ( $z$ -component of spin equal to  $+\frac{1}{2}\hbar$ ) or spin down ( $z$ -component of spin equal to  $-\frac{1}{2}\hbar$ ) – but no longer a superposition of the two.

Wavefunction collapse is not well understood, although a great deal of work has gone into this problem. There is no quantum interaction acting on a system, which effects a transition from a quantum superposition in which a system does not possess well-defined values for certain properties, to a **classical probabilistic state** in which the system does indeed possess well-defined values for these properties albeit with different probabilities. As an example, such a classical probabilistic state describes the situation in which you spin a coin and cover it with your hand without looking at it. We know that the coin is either “heads up” or “tails up” but we do not know which. This is fundamentally different from a quantum superposition of “heads up” and “tails up” in which the coin would not be either “heads up” or “tails up” but both at the same time.

As we have explained above, one can choose to measure one property or another. For example one can choose to measure accurately the position of a particle, in which case the environment includes an apparatus for the accurate measurement of position and the measurement induces wavefunction collapse into a state of well-defined position, or one can choose to measure accurately the momentum of a particle in which case the environment includes an apparatus for the accurate measurement of momentum and the measurement induces wavefunction collapse into a state of well defined momentum (but we cannot do both simultaneously). For an electron (or other particle with spin) one can measure the component of spin in the  $z$ -direction, in which case the environment includes a Stern-Gerlach apparatus with its magnetic field in the  $z$ -direction and after passing through the apparatus the wavefunction for the particle collapses either into one describing a spin up particle or into one describing a particle spin down particle. Alternatively we may choose to measure the component of spin in the  $x$ -direction in which case the environment includes a Stern-Gerlach apparatus with its magnetic field in the  $x$ -direction and after passing through the apparatus the wavefunction for the particle collapses either into one describing a particle whose  $x$ -component of spin is  $+\frac{1}{2}\hbar$  or into one describing a particle whose component of spin in the  $x$ -direction is  $-\frac{1}{2}\hbar$ . However, we cannot perform these two experiments simultaneously. At the end of the last section, we explained what happens when these two experiments are performed sequentially - the interaction of the spin-one half particle with the first apparatus

affects is spin state and consequently alters the results of the second experiment.

It is tempting and comforting to interpret this very strange behaviour of sub-microscopic systems in terms of so-called “hidden variables”. This is the proposition that a particle *does* indeed possess both position and momentum or a component of spin both in the  $z$ -direction and the  $x$ -direction, but that the experimentalist does not know what the values of any of these quantities are until (s)he performs an experiment to measure it. As we shall see later, this is not the case - it was shown by John Bell that this postulate gives results which are not consistent with the predictions of Quantum Mechanics. We have to accept the fact that at the sub-microscopic level a system simply does not possess these quantities and that the act of measurement - or the interaction of the system with a macroscopic environment - changes the wavefunction. Quantum Mechanics permits one to determine the probability that a measurement will yield a given result (e.g. an electron which has passed through a Stern-Gerlach apparatus with its magnetic field in the  $x$ -direction and subsequently through a Stern-Gerlach apparatus with its magnetic field in the  $z$ -direction has a probability of  $\frac{1}{2}$  to give a result  $+\frac{1}{2}\hbar$  and a probability of  $\frac{1}{2}$  to give a result  $-\frac{1}{2}\hbar$ ). This means that if we perform the experiment one hundred times, we expect that within statistical errors, we will get on average  $+\frac{1}{2}\hbar$  fifty times, and  $-\frac{1}{2}\hbar$  fifty times. However we cannot predict what the result will be for any one measurement - very simply because before the measurement is effected, the particle does not possess a component of spin in the  $z$ -direction.

## 12.1 Decoherence

Wavefunction collapse is the mechanism in which a system, by interacting with its environment (which includes a measuring apparatus), is transformed from a superposition of states into a definite (classical) state with a well-defined value of a given measurable quantity. This mechanism is not understood, although significant progress has been made in recent years. It is the property of a wave that leads to interference which gives rise to the strange phenomenon that permits a quantum system to simultaneously possess several (often an infinite number) of values for a particular measurable property. This property is called “coherence” and is related to the fact that the phases of two waves that interfere have to be “locked” so that there is a constant phase difference between them which generates this interference. The process of unlocking this phase - so that the phase difference of the two waves is randomized is known as “**decoherence**” and this is now believed to be the mechanism that leads to wavefunction collapse. When decoherence occurs, the quantum property of superposition of states, with many different possible values for a given quantity, is lost - the wavefunction has collapsed into the wavefunction for a state in which that quantity is indeed well-defined and has a unique value.

Monochromatic (single wavelength) light, or other monochromatic electromagnetic radiation, or particles with the same momentum, used in the Young’s double slit experiment, can interfere (giving rise to interference patterns) because the incident wave is coherent, that is to say the wavefront at the double slits has peaks and troughs at the same time (or at least with a fixed time interval between them) - they are phase locked. If something

happens to randomize the phases of the wave incident on the two slits, the interference is lost (decoherence has occurred). The attempt to determine through which slit a photon or electron has passed is an example of a disturbance of the system which leads to decoherence and consequently loss of the interference pattern.

Decoherence was introduced in Quantum Physics by Dieter Zeh in 1970 [28] and developed in the 1980's. The idea is that when a sub-microscopic system which is in a superposition of states interacts with a macroscopic environment, the evolution in time, determined by Quantum Mechanics, will change the entire system (the original sub-microscopic system plus the environment) into a different superposition of states of the entire system, i.e the sub-microscopic system plus the environment. Subsequently a measurement which selects a particular state of the environment automatically selects a particular state of the sub-microscopic system. As an example, suppose the sub-microscopic system is the spin of an electron which is in a state which is a superposition of spin-up and spin-down,

$$a\Psi_{\uparrow} + b\Psi_{\downarrow},$$

and the environment is a detector which has two states which we call "red" and "green". If the environment is in state "red" then a light shines red and if it is the state "green" the light shines green.

Suppose that we start off with the detector light "red". We need to consider the microscopic system (the electron in a superposition of spin-up and spin-down *together* with the detector in the state "red". The wavefunction of the combined system is,

$$a\Psi_{\uparrow}\Psi_{\text{red}} + b\Psi_{\downarrow}\Psi_{\text{red}}$$

Interference is possible between these two components of the wavefunction and because of this the electron is *not* in the state of spin-up *or* spin-down but spin-up *and* spin-down. We have difficulty in imagining or understanding this, but it doesn't matter, because in a short time (much shorter than the smallest time interval of which we can be conscious) the wavefunction evolves following the time-evolution determined by the Schrödinger equation<sup>15</sup> into a final state

$$a\Psi_{\uparrow}\Psi_{\text{red}} + b\Psi_{\downarrow}\Psi_{\text{green}}.$$

Now the detector is such that whereas the wavefunction components  $\Psi_{\uparrow}$  and  $\Psi_{\downarrow}$  can interfere with each other the detector states  $\Psi_{\text{red}}$  and  $\Psi_{\text{green}}$  are sufficiently different that interference between them is impossible (or at least so unlikely that it essentially never happens). In that case the components of the wavefunction  $\Psi_{\uparrow}\Psi_{\text{red}}$  and  $\Psi_{\downarrow}\Psi_{\text{green}}$  do *not* interfere and the wavefunction describes a system which we can understand, namely a classical probabilistic state. Observation of the detector (observing whether the light is red or green) then determines if the electron is spin-up or spin-down. The probability that the result is found

---

<sup>15</sup>The system which includes the macroscopic detector is far too complicated for us ever to be able to solve the Schrödinger equation of the combined system, but the decoherence is assumed to proceed through the development of the combined wavefunction of the microscopic system and the macroscopic detector, determined by usual quantum physics.

to be spin-up, i.e the probability that the light is red is  $a^2$  - and similarly the probability that the result is found to be spin-down, i.e the probability that the light is green is  $b^2$ .

The rate at which this decoherence takes place depends on a number of properties of the environment - such as its temperature - but estimates of the decoherence time have suggested that for macroscopic systems, the time-scale for such a decoherence process is too short for any interference to occur (two waves can only interfere if they remain coherent for a period which is much longer than the period of the waves)– which is why we do not observe quantum behaviour in macroscopic objects.

Decoherence does not lead directly to wavefunction collapse. It does not directly explain why a measurement returns a particular value of a property of a quantum system, despite the fact that the system was initially in a state for which that value was not defined. It does, however, provide us with a mechanism which explains how the interaction of a quantum system with its environment can transform a system from the unintelligible superposition to a standard (classical) probability distribution.

Incidentally, one of the properties of the time evolution of a wavefunction in quantum physics is that interference never totally disappears. What actually happens is that there are very many different states that the individual atoms in the detector can be in when the detector light is red and similarly many different states that the individual atoms in the detector can be in when the detector light is green. The detector will end up in a quantum superposition of these many “red” states *or* in a quantum superposition of these many “green” states. These superpositions interfere among themselves, so that what actually happens when a microscopic system in a given quantum state interacts with its macroscopic environment is that the interference between the different initial microscopic states is transferred to interference between different states of the environment. If the environment possesses some property (e.g. the colour of the light) for which there is no interference between states of the detector with different values of this property, then the observation of that property constitutes a measurement of the state of the microscopic system after decoherence.

## 13 Interpretations of Quantum Physics

### 13.1 Copenhagen Interpretation

The Copenhagen interpretation of Quantum Physics was developed by Niels Bohr and his assistant, Werner Heisenberg, between 1925 and 1927 [29]. It is based on the proposition that Physics is the Science of measurement and that a measurable quantity has no reality until it is measured. In the Copenhagen interpretation, one applies the rules of Quantum Mechanics to sub-microscopic systems but not to the measuring device, which is a macroscopic object that has the property (for reasons which are not understood) of effecting wavefunction collapse from a quantum superposition to a classical probabilistic state.

It is for this reason that a system can be in a superposition of several (or even an infinite number of) states in which a given measurable quantity takes on different values. Once a measurement is performed the wavefunction collapses to what Bohr described as a classical state – i.e. one can apply classical physics to the system after measurement.

Importantly, this means that questions that we are aching to ask, such as “which slit did the electron go through in Young’s (electron) double slit experiment?” may not be asked by a physicist, since in the interference experiment we do not observe which slit the electron passed through. A philosopher is, of course, at liberty to ask any question (s)he likes, but a physicist may only ask questions to which the answer has (at least in principle) been determined by a measurement.

Until the late 1950’s this was accepted as the standard interpretation of Quantum Physics, although as we shall see below, when taken to extremes it can lead to absurdities.

### 13.2 Many Worlds Interpretation.

An alternative to the Copenhagen interpretation of Quantum Physics is the “Many Worlds Interpretation”, first proposed by Hugh Everett [30] in 1957 and further developed by Bryce de Wit in the 1960’s and 1970’s [31].

This interpretation dispenses with the arbitrary distinction between the sub-microscopic and macroscopic (measuring apparatus), insisting that everything including the measuring apparatus and the observer must be treated as a Quantum system and that wavefunctions should be a wavefunction for the entire Universe. There is therefore no such concept of wavefunction collapse, although the Many Worlds Interpretation makes use of the idea of decoherence, which is explained in terms of quantum interaction between sub-microscopic systems and their environment.

Instead of arguing that the wavefunction collapses when a measurement is made the Many Worlds interpretation argues that each time an observation is made, the entire Universe splits into many Universes in which each possible outcome for the result of the observation occur. The probability of a particular outcome is reflected in the number of Universes in which that