# 14 Two Enigmatic "Thought Experiments"

## 14.1 Schrödinger's Cat

The famous Schrödinger's cat experiment is a thought experiment conceived by Erwin Schrödinger in 1935 [32] to demonstrate that the Copenhagen interpretation of Quantum Physics leads to an absurdity.

An atom of a **radioactive** substance decays into its radioactive products, but we do not know exactly when this will happen. In keeping with the Copenhagen interpretation, this means that the atom is in a state which is a superposition of the parent atom and the daughter atom, until such a time that an observation is made on the atom to see if it has indeed decayed or is still in its initial state.

At the level of one atom, a superposition of two or more states is something that we have to live with and accept the fact that our experiences of the macroscopic world are simply inapplicable at the level of a single atom. But now imagine that this atom is coupled to the following macroscopic system.

1. **A Geiger counter**,
2. An electronic hammer which is triggered when the Geiger counter clicks,
3. A vial of a poisonous gas which is broken when the hammer is triggered,
4. A cat placed close to the vial of poison.

The entire system is placed in a box which is isolated from any observer.

A cartoon drawing of the experimental setup is shown in Fig. 41. The decay of a single radioactive atom causes the Geiger counter to click, which in turn causes the hammer to smash the vial, which in turn releases the poisonous gas, which in turn kills the cat (it is not known why Schröinger chose a cat - *note* that this was a "thought" experiment - physicists do not conduct cruel experiments on animals!).

If the atom has decayed, the wavefunction for the entire system is in state 1, whose wavefunction, $\Psi(1)$, is the product of the wavefunction for each element:

$$\Psi(1) = \Psi(\text{decayed atom}) \times \Psi(\text{clicked Geiger counter}) \times \Psi(\text{vial smashed by hammer}) \\ \times \Psi(\text{poisonous gas released}) \times \Psi(\text{cat dead})$$

On the other hand if the atom has not yet decayed the system, it is in state 2, whose wavefunction, $\Psi(2)$, is given by

$$\Psi(2) = \Psi(\text{atom in its initial state}) \times \Psi(\text{Geiger counter unclicked}) \times \Psi(\text{hammer poised}) \\ \times \Psi(\text{poisonous gas confined to vial}) \times \Psi(\text{cat alive})$$

Figure 41: Schrödinger's cat experiment. The decay of a radioactive atom causes a Geiger counter to click, which releases a hammer, which smashes a vial of poison an kills the cat. Whilst the system is not observed and the atom is in a superposition of the parent atom and radioactive daughter, the cat is in a superposition of being alive and dead.

Since the entire system is enclosed in a box which is isolated from any observer then according to the Copenhagen interpretation the entire system must be in a superposition of these two states

$$a\Psi(1) + b\Psi(2),$$

where $a^2$ and $b^2$ are the probabilities that an observation of the system will find the cat to be dead or alive. This interpretation forces us to conclude that until such an observation is made the cat is in a superposition of being dead and alive, i.e. the cat is both dead and alive, until an observer chooses to open the box and observe the cat.

This thought experiment was rendered even more absurd by a refinement suggested by Eugene Wigner [33]. He suggested putting a friend in the box with the cat (protected from the poison). While the box remains closed the friend can observe the cat and for him (her) the wavefunction for the system either contains a live cat or a dead cat. But for the observer outside the box the wavefunction is still a superposition. This implies that the wavefunction for a system depends on the interaction of the system with the consciousness of the observer.

The difficulty lies in the fact that in the strict Copenhagen interpretation, wavefunction collapse only occurs when an observation (or measurement) is conducted. Nowadays, we would argue that wavefunction collapse occurs whenever there is interaction between a sub-microscopic quantum system and its macroscopic environment, which leads to decoherence. Thus, although a single atom can be considered to be in a superposition of "decayed" and "not decayed", the other devices in the thought experiment, whether or not they involve an actual observation of the cat, provide a macroscopic environment which induces wavefunction collapse. This point of view at least separates the concept of wavefunction collapse from the interaction of a system with the consciousness of the observer, in keeping with the usual scientific approach to Nature as being objective and disconnected from the mind of the experimentalist.

## 14.2 Einstein Rosen Podosky (EPR) Paradox - entanglement

In 1935, Albert Einstein, Boris Podolsky and Nathan Rosen (EPR) [34] proposed a thought experiment which claimed to show that Quantum Mechanics was either incomplete or inconsistent with the results of Special Relativity.

They considered a particle at rest decaying into two identical particles. By conservation of momentum, these two decay particles must have equal and opposite momentum - so that one moves towards observer Alice and the other towards observer Bob. The momentum of the particles is not known, but we know that once we have measured the momentum of one of them, we know the momentum of the other. Thus, when Alice measures the momentum of her particle its wavefunction collapses into a wavefunction for a particle with well-defined momentum. Because the momenta are **correlated**, this means that the wavefunction of Bob's electron, which is some distance away, also collapses at the same time. This implies what EPR called "spooky action at a distance" – and is supposed to be forbidden by Special Relativity, which tells us that nothing can travel faster than light.

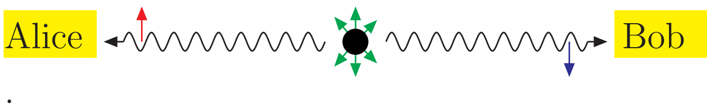


Figure 42: A particle with no spin decays into two electrons, one of which is observed by Alice and the other by Bob. If Alice measures the component of spin in a given direction and finds that it is spin up, then she knows for certain that a measurement of the component of Bob's electron in that direction will show it to be spin down (or vice versa).

Although EPR considered the position or momentum of a particle, which, according to Heisenberg's uncertainty principle, cannot be measured simultaneously, it turns out to be clearer if we consider a two-state system such as the spin of an electron. In analogy with the fact that one cannot determine the position and momentum of a particle with arbitrary accuracy and that a measurement of one or the other alters the wavefunction, we cannot measure the component of spin of a particle in more than one direction. The act of measuring the spin of the electron, thereby obtaining a given result (up or down) for the spin component in that direction, collapses the wavefunction into one which describes an electron with that particular value for the component of spin in that direction.

Now let us consider a particle at rest with no spin, that decays into two electrons moving in opposite directions - one towards the experimentalist Alice and the other towards the experimentalist Bob. By conservation of spin we know that if Alice's electron is spin up (measured in any direction) the Bob's will be spin down and vice versa. This is demonstrated in Fig. 42. However, before any such measurement is made we do not know which of these results will be found - it could be either way. The state of the two electrons considered together is a superposition of these two possible outcomes, written as

$$\frac{1}{\sqrt{2}}\left(\Psi^A_\uparrow\Psi^B_\downarrow - \Psi^A_\downarrow\Psi^B_\uparrow\right)$$

(where the superscripts $A$ and $B$ refer respectively to Alice's and Bob's electron). Such a wavefunction describes what is called an **"entangled state"**[16] as it cannot be factorized into a wavefunction describing Alice's electron multiplied by a wavefunction describing Bob's electron. Note that this does not mean *either* Alices's electron is spin up and Bob's is spin down *or* vice versa but that the two electrons are in a state which is a superposition of both possibilities.

If Alice measures the component of spin of her electron in some direction and finds it to be $+\frac{1}{2}\hbar$, then the wavefunction for the two electrons collapses into the state $\Psi^A_\uparrow\Psi^B_\downarrow$ whereas

[16] The state of the system in the Schrödinger's cat experiment is also an entangled state as it is a superposition of a state in which the atom has not decayed, the Geiger counter has not clicked $\cdots$ and the cat is alive, and the state in which the atom has decayed $\cdots$ and the cat is dead.

if she finds it to have component $-\frac{1}{2}\hbar$, then the wavefunction for the two electrons collapses into $\Psi^A_\downarrow \Psi^B_\uparrow$ .

Whatever the result of Alice's measurement is, the wavefunction not only for her electron but also for Bob's electron is instantaneously altered. EPR argued that this constituted an instantaneous action at a distance, which violates the principles if Special Relativity.[17]

EPR concluded that the only possible resolution of this "paradox" was that the two electrons did indeed possess a well-defined value for the component of spin in any direction (Alice's and Bob's electron spin in that direction would always be opposite), but that Quantum Physics was incomplete in that it did not permit one to determine what these values were. Such an interpretation is known as the "hidden variable" theory, and whereas it is easier for us to comprehend because it relates directly to similar experiences we have in the macroscopic world, it turns out to be inconsistent with the predictions of Quantum Physics.

[17] Ironically, Einstein misunderstood his own theory, which does not forbid action at a distance as long as this cannot be used to transmit information faster than the speed of light. There is no way that Alice can use her measurement to send a message to Bob (e.g. spin up means "yes" and spin down means "no") as she does not know, a priori, what the result of her measurement will be. The wavefunction for an entire extended system collapses instantaneously when a measurement is performed, but no part of the extended system actually communicates with another part.