Schrödinger's Cat States

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Recently, a group of scientists (see Monroe and others in Suggested Reading) of the National Institute of Standards and Technology (NIST) have reported that they have generated at the single atom level 'Schrödinger cat' like states of matter. This is indeed exciting when it is realised that such states which entangle macroscopic behaviour of matter with quantum states of atoms were conceptualised in a thought experiment more than sixty years ago by Erwin Schrödinger (see Schrödinger in Suggested Reading). He had put forward the wave mechanics version of quantum mechanics to explain the nature of matter on the atomic scale but had philosophical objections to the probabilistic interpretation given by the Copenhagen School (see Bohr in Suggested Reading) to the solutions of his wave equation. To proceed further in our attempt to appreciate the significance of the experiment carried out by Monroe and his colleagues, it is necessary that we understand Schrodinger's cat paradox and Schrödinger's cat states.

Schrödinger's Cat Paradox

As we know, Newtonian classical mechanics is deterministic. The time evolution of a system can be completely predicted once the solution of the equation of motion is fixed by giving the state of the system at an initial time. Also, ideally a classical system can be observed without disturbing the state of the system. In contrast to these properties of classical systems the time evolution of quantum systems is given by the solutions of Schrödinger's wave equation. These solutions are called *wave functions*. They can be expanded in terms of superposition of observable states called the *eigen states*. With the wave functions, only probabilities can be associated for finding the system in different eigen states of the observable physical quantities. The act of observing a quantum system inevitably disturbs the system and one of the eigen states is selected. This is also described as the collapse of the wave function to one of the allowed quantum states. For bringing out the absurdity in the probabilistic interpretation of his wave function, Schrödinger concocted a diabolic thought experiment which we describe next.

He visualised a cat placed in a closed chamber in which a radioactive atom is used to trigger a device that will release poison inside the box (*Figure 1*). To make the argument simple Schrödinger suggested that an atom which has equal probability of emitting an electron in one hour and of remaining undecayed be placed inside the box with the cat. The emitted electron as it carries an electric charge is planned to trigger a Geiger Mueller (GM) counter, which can give a surge of voltage that can open a phial containing poison. It is therefore expected that if the atom has decayed during the hour the cat would have died due to the release of the poison from the phial. If the atom has remained undecayed

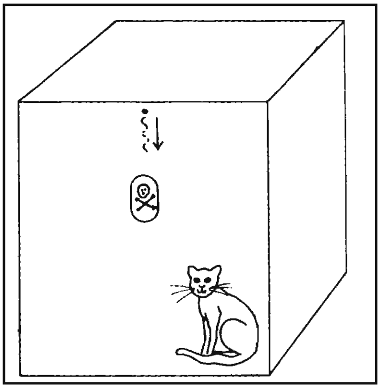

Figure 1. The box containing the cat, the radioactive nucleus and the poison.

the cat would be found alive when the box is opened. The probability of finding the cat alive or dead on opening the box after one hour is half. There is no paradox so far. The paradox arises when we describe the state of the unobserved system.

Let the quantum states of the atom which correspond to its decay by emission of an electron by it and the other which corresponds to it having remained undecayed be denoted by $\psi_\downarrow$ and $\psi_\uparrow$, respectively. Let us symbolically denote the dead and alive states of the cat by the symbols Ξ_{dead} and Ξ_{alive}, respectively. Therefore, the two states of the total system which combine the states of the radioactive atom with the dead and alive states of the cat are $\Xi_{dead}\Psi_\downarrow$ and $\Xi_{alive}\Psi_\uparrow$ respectively. According to the quantum superposition principle the unobserved state of the box before it is opened will be given by the following expression:

$$\Sigma=(1/\sqrt{2})\,\Xi_{dead}\,\psi_\downarrow + (1/\sqrt{2})\,\Xi_{alive}\,\psi_\uparrow\,.$$

Such a state is called a *Schrodinger's cat* state. This is the unobserved state of the system, i.e. the state of the system before the box has been opened at the end of the one hour period. As can be seen from the expression above, Σ describes the strange-ness of the quantum world. States such as that of Schrödinger's cat entangled with quantum states have no reality. According to the Copenhagen interpretation of the Schrödinger cat state, an unobserved cat inside the box is neither dead nor alive. The radioactive decay has neither happened nor not. The way to get out of this paradoxical situation is to accept the quantum mechanical framework that nothing is real unless it is observed. When the system is observed and the cat is found dead one would have also found that the radioactive atom has decayed, and if the cat is found alive the radioactive atom would have been found to have remained undecayed. Although physicists could get out of the paradox by avoiding the question on the state of the unobserved system, the interest remained to find whether states like Σ can be produced in real experiments. The results reported by Monroe and others show that it is possible to entangle the electronic quantum states of an atom with classical-like wave packet states such that the state of the system looks like Σ, the Schrödinger cat like state. We next give in brief the main features of the NIST experiment.

Two Atoms in One

In the NIST experiment a ^{9}Be neutral atom is made to drift in an electromagnetic trap (see Monroe and others (*Phys. Rev. A*) in Suggested Reading) and one of its electrons is stripped off to confine the ionised atom electromagnetically by a harmonic force. By laser cooling the single $^9Be^+$ is made to oscillate in the quantum level corresponding to the zero-point energy of the harmonic oscillator (see Monroe and others (*Phys. Rev. Lett.*) in Suggested Reading). In this situation the ion settles virtually motionless at the centre of the trap. The $^9Be^+$ can exist in two hyperfine ground states (denoted by $\psi_\downarrow$ and $\psi_\uparrow$, respectively). The two states, which we may call spin-down and spin-up, are separated in frequency by about 1.250 GHz. At any one time the ion has equal chance of being in one of the two states. The ion in the two states is pushed apart by applying a pair of laser beams, called 'force beams', which drive the harmonic oscillator at the natural vibrational frequency of the trap. Each force sets the ion in motion with the spin-up and the spin-down state, respectively. The result is that two wave packets which are tied up to one or the other of the hyperfine internal states of the ion begin to oscillate with phase difference of π The amplitude of oscillations of the wave packets is measured by adjusting the phase of the force lasers until they overlap and interfere with each other.

In the experiment the individual wave packets which were of size around 7nm could be pushed apart by as much as 80nm (*Figure 2*). Although we have two localised wave packets, there is only one atom! The Schrödinger cat like states are formed. This is similar to the situation encountered by Schrödinger in his thought experiment. We bring out this analogy.

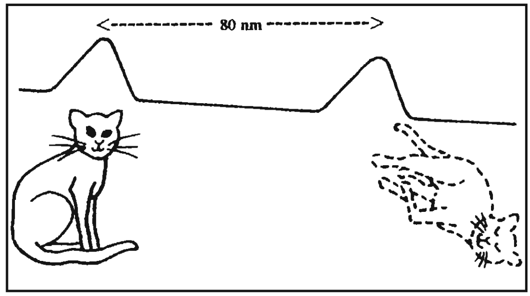

Figure 2. Wave packets entangled with the electronic states of the ion can be apart by as much as 80nm and thus have some quantum - classical features of the Schrodinger cat states.

If the localised wave packets are described by their position wave functions $\Xi_{x\,(1)}$ and $\Xi_{x\,(2)}$ and the two electronic states of the ion by $\psi_\downarrow$ and $\psi_\uparrow$, the Schrodinger cat like state produced by Monroe and others is described by the wave function Σ_{NIST},

$$\Sigma_{NIST} = (1/\sqrt{2})\, \Xi_{x\,(1)}\, \psi_\downarrow + (1/\sqrt{2})\ \ \Xi_{x\,(2)}\, \psi_\uparrow .$$

The authors point out that the evolution of the position-space wave packets with time has the appearance of a rolling marble in a bowl, which to an observer may seem like two marbles rolling back and forth in opposite directions and at times appearing simultaneously at each edge of the bowl. The existence of the superposition given above has been verified by detection of the quantum mechanical interference between the localised packets. The technology of producing such states and their possible applications go beyond the scope of this article.

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References

- N Bohr. *Nature.* 121. 580, 1928; *Phys. Rev.* 48. 696, 1935.
- E Schrödinger. *Naturwissenschaften.* 23. 807, 1935. translation in J A Wheeler and W H Zurek. Eds. *Quantum Theory and Measurement.* Princeton University Press. Princeton. NJ, 1983.
- C Monroe and others. *Phys. Rev. A* 51. 3112, 1995.
- C Monroe and others. *Phys. Rev. Lett.* 75. 4011, 1995.
- C Monroe and others. *Science.* 272. 1131, 1996.

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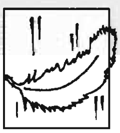

"It must have taken an awful lot of genetic engineering to develop sheep which produce sweaters instead of wool"

"Sure, but it was even more difficult to get the 'Lacoste' trademark on them".

From: *Gene Antics*