Stephen Hawking: "When I hear of Schrödinger's cat, I reach for my gun"

$$\psi = \frac{1}{\sqrt{2}}\left(\psi_{\text{dead-cat}} \cdot \chi_{\text{atom-decayed}} + \psi_{\text{alive-cat}} \cdot \chi_{\text{atom-excited}}\right) \; ?$$

Note that Schrodinger was attempting to made a clearly absurd example in order to argue that the standard interpretation of quantum mechanics is nonsense.

$$\psi = \frac{1}{\sqrt{2}}\left(\psi_{\text{dead}} + \psi_{\text{alive}}\right)$$

- This equation is absurd for many reasons, including
  - A cat is *not* a reversible Hamiltonian system; it is a macroscopic system that is undergoing numerous irreversible processes and is interacting constantly with the environment.
  - There is not *even in principle* a Hamiltonian such that

$$H\psi_{\text{cat}} = i\hbar \frac{\partial}{\partial t}\psi_{\text{cat}}$$

  - This has *nothing* to do with life or consciousness. Even an inanimate Geiger counter cannot be considered to be in a pure quantum state. When it fires, the avalanche of charge is clearly an irreversible process.
- Therefore, one has to think about the quantum measurement process more deeply. It is not helpful to write equations that treat macroscopic, non-isolated systems as if they were simple pure quantum states.

- Remember that a macroscopic system is generally in a configuration (such as "alive" or "needle pointing left") that could be described by something like N_A factorial quantum states. ***In general, every macroscopic observable corresponds to an enormous number of different quantum states, all of which must be considered when calculating an expectation value.***

- When a pure quantum mechanical state interacts with a macroscopic system, the quantum coherence is lost. That is an experimental fact that can be both observed and understood theoretically (see below).

- Recall that a signature of two interfering states is a cross term, such as in

$$\psi = \psi_A + \psi_B$$

$$|\psi|^2 = |\psi_A|^2 + |\psi_B|^2 + 2\operatorname{Re}\psi_A^*\psi_B$$

- Suppose that we chose our basis states here such that A and B interact very differently with some macroscopic system (detector).

- When this QM state interacts with the macroscopic system of some 10^{23} degrees of freedom, the two eigenstates A and B will follow separate irreversible paths and the interference term will become unobservably small. To see the effects of the interference continuing after the measurement process would be similar in probability to seeing all of the air molecules in the room suddenly go left and right, leaving the middle 1/3 of the room in vacuum.

Consider an entangled quantum state and the expectation value of some operator Q (e.g. spin or position)

$$\psi = \alpha|\psi_A\rangle + \beta|\psi_B\rangle$$

$$\langle Q \rangle = \alpha Q_A + \beta Q_B + 2\,\mathrm{Re}\,\alpha^* \beta \langle \psi_A |Q| \psi_B \rangle$$

interference

Now imagine the quantum system interacting with the environment, which is some sort of experimental measurement apparatus. In principle it is described by a (very complex) wave function.

$$|\mathrm{Env}\rangle$$

See Wojciech Zurek, *Decoherence and the Transition from Quantum to Classical*, Physics Today, October 1991.

Before there is any interact, the quantum system and environment are separate, so the total wave function factorizes:

$$|\mathrm{Before}\rangle = \left[\alpha|\psi_A\rangle + \beta|\psi_B\rangle\right]|\mathrm{Env}\rangle$$

But after the interaction the wave functions are entangled. The environment interacts differently with the two states, as expected for a measurement apparatus designed to distinguish them.

$$|\mathrm{After}\rangle = \alpha|\mathrm{Env}_A\rangle + \beta|\mathrm{Env}_B\rangle$$

Now, the environment is so complex with $\cong N_A$ d.o.f. that the interaction is chaotic and irreversible, causing A and B to diverge exponentially very rapidly in phase space until there is very little overlap between them:

$$\langle \mathrm{Env}_B | \mathrm{Env}_A \rangle \approx 0 \to 0 \text{ as number d.o.f.} \to \infty$$

$$\langle \mathrm{Env}_B |Q| \mathrm{Env}_A \rangle \approx 0 \to 0 \text{ as number d.o.f.} \to \infty$$

$$\langle Q \rangle \to \alpha \langle \mathrm{Env}_A |Q| \mathrm{Env}_A \rangle + \beta \langle \mathrm{Env}_B |Q| \mathrm{Env}_B \rangle$$

We (almost) never see an interference term after the interaction with the environment.

For more mathematics on how the effects of quantum interference terms disappear rapidly when a pure quantum state interacts with a system with a macroscopic number of degrees of freedom. See for example:

http://en.wikipedia.org/wiki/Quantum_decoherence

and the references therein.

Serious theoretical and experimental work in this field continues (See Serge Haroche, ENTANGLEMENT, DECOHERENCE AND THE QUANTUM/CLASSICAL BOUNDARY, Physics Today, July 1998). There remains much to learn in detail about the decoherence or quantum-measurement process, building on much work done in past decades. It can be particularly interesting in a practical sense for quantum computing!

This work probably cannot remove some *philosophical* questions, but scientific, physics questions *are* being answered, with much progress made since Copenhagen!

Quantum "measurement problem" See Stephen Adler, arXiv:quant-ph/0112095, *Why Decoherence has not Solved the Measurement Problem.*

Decoherence theory explains why we never see complex macroscopic systems in superposition states with observable quantum interference terms, but it does not offer any explanation of how for a given instance the system "decides" which outcome to take out of all possibilities or even why we experience just one of the possibilities.

In a Stern Gerlach experiment with a beam of spins polarized in the z direction, suppose we measure the spin along x. QM tells us we get a 50% chance of up $(+x)$ versus down $(-x)$. But for a single electron, how does it choose to be up or down, and why do we observe only a single outcome?

No one has a clear answer, and the discussion becomes more philosophical than physical, as alternative views never offer any difference at an observational level.

What is clear and is fascinating (to me) is that nature at a fundamental level apparently operates with truly random variables.

Consider a decaying nucleus, as in Schrodinger's cat's box.

Or equivalently a muon decaying to an electron and two neutrinos. The probability that the muon will decay in the next nanosecond is a constant completely independent of when it was created (in pion decay), where it is, what is around it, etc. Nothing is getting old or winding down in the muon as time progresses.

Mathematically the decay process is, to the precision that anybody has managed to measure, a purely Poisson random variable. Consequently, in an ensemble of nuclei or muons the number remaining undecayed will decrease exponentially, as is observed for all particle and nuclear decays.

All evidence points to the chance that our muon will decay in the next nanosecond as being completely random, with *no mechanism internal or external to the muon being responsible*.

"God" *does* play dice!

New from Oxford University Press

QUANTUM ENIGMA

PHYSICS ENCOUNTERS

CONSCIOUSNESS

BRUCE ROSENBLUM

FRED KUTTNER

If the entire universe is a quantum system, where does the superposition of states really end?

Does "consciousness" finally collapse the wave function?

Famous physicists like Wigner considered this (and ultimately rejected it as nonsense), but this discussion keeps resurfacing. . .

Note: Kuttner and Rosenblum insist to me that they never advocate the view that consciousness is responsible for collapsing the wave function, but this book certainly hints rather strongly at that point of view.

From Griffiths:

"I would not pretend that this is an entirely satisfactory resolution, but at least it avoids the *stultifying solipsism* of Wigner and others, who persuaded themselves that it is the involvement of human consciousness that constitutes a measurement in quantum mechanics."

Solipsism: in philosophy, the theory that only the self exists, or can be proved to exist.

Stultify: to render absurdly or wholly futile or ineffectual, esp. by degrading or frustrating means

References:

- Available also in the eCommons 139B site:
  - Wojciech Zurek, *Decoherence and the Transition from Quantum to Classical*, Physics Today, October 1991.
  - Wojciech Zurek, *Decoherence and the Transition from Quantum to Classical, Revisited,* Los Alamos Science **7**, 2002.
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