PERSPECTIVES: QUANTUM MECHANICS

Schrödinger's Cat Is Out of the Hat

Claudia Tesche

Quantum mechanics is one of the most remarkable achievements of 20th century physics. The quantum mechanical formalism has been extraordinarily successful in accounting for a wide range of microscopic phenomena, from the interactions of subatomic particles to the structure of atoms and molecules and the interaction of light with matter. But can quantum theory also be used to describe the behavior of macroscopic objects? It would be satisfying if the answer to this question were yes. Given that atoms and molecules are the constituents of macroscopic objects, a quantum description of aggregates of billions of these entities would provide a seamless, elegant description of matter. On page 773 of this issue, van der Wal *et al.* (*1*) take an important step toward demonstrating that quantum mechanics does provide a satisfactory description of macroscopic phenomena.

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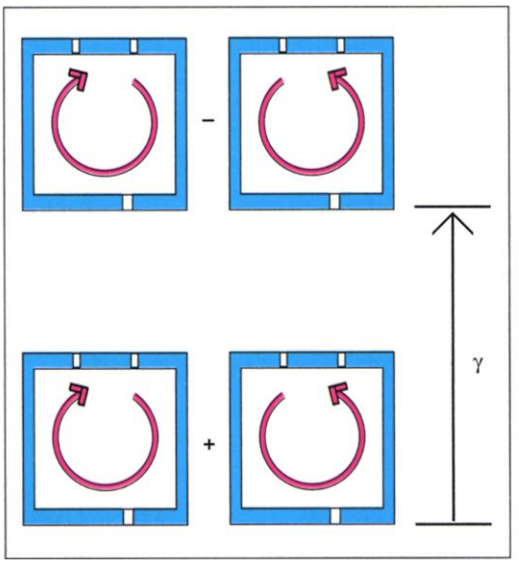
The application of quantum mechanics to complex systems has been the subject of great controversy since quantum theory was developed in the 1920s. The key stumbling block has been that the predictions of quantum mechanics are in total conflict with what our intuitions tell us about the properties of macroscopic objects. In our experience, everyday objects have well-defined and unique physical properties—cats are either alive or dead, not both at the same time—and we expect these properties to endure even when no one is there to observe them.

This state of affairs is not at all typical of quantum systems: A microscopic particle such as an electron may be simultaneously in multiple states that have very different, apparently mutually exclusive physical properties. This situation may appear relatively benign when the property in question is something as esoteric as the "spin" of an electron. But one of the founders of quantum theory, Erwin Schrödinger, suggested a much more alarming scenario. In his classic 1935 gedanken experiment, the quantum system was to be his cat, and the properties in question were desperately different, that of being "dead" and "alive." In the gedanken experiment, the imaginary cat is placed in a box with a radioactive substance. The box also contains a mechanism that releases poisonous gas when triggered by the presence of radioactive decay products. According to our classical view of events, a radioactive decay would kill the cat, even though we may not be aware of its fate. Schrödinger claimed that an entirely quantum mechanical description would couple together the state of the radioactive nucleus and the fate of the cat. Both would remain in limbo until the box was opened by the experimentalist.



A benchtop version of Schrödinger's famous cat. A superconducting loop supports a circulating current of either clockwise or counterclockwise orientation. At appropriate magnetic field bias, the ground state is a symmetric superposition of the two current orientations (**bottom**). The first excited state corresponds to the antisymmetric combination (**top**). Transitions between the ground and first excited state occur by absorption of a photon of microwave radiation (indicated by γ).

The van der Wal version of Schrödinger's cat in the box consists of a set of two nested superconducting devices (see the figures). The inner loop is a macroscopic analog of Schrödinger's unfortunate feline. The clockwise and counterclockwise directions of the current flow in this loop correspond to Schrödinger's states, "dead" and "alive." The outer loop is a SQUID (superconducting quantum interference device) that measures the direction of the current flow in the inner loop.

Superconductivity is essentially a quantum phenomenon. Electrons in superconducting materials tend to pair up, forming a single quantum entity. At low enough temperatures, all pairs coalesce into a ground state that can support a persistent current indefinitely. The currents indicated in the first figure are of exactly this nature. Van der Wal *et al.* applied a magnetic flux to the inner loop to ensure that the system could support clockwise and/or counterclockwise currents of about equal amplitudes. Small changes in the applied magnetic field will perturb the quantum mechanical wave function of the electron pairs slightly and thus alter the amplitude of the circulating current. This behavior reflects microscopic, rather than macroscopic, quantum phenomena.

The near degeneracy between the clockwise and counterclockwise flow in van der Wal's experiment opens up a much more interesting possibility, namely that of observing the quantum mechanical superposition of the two superconducting condensates. The ground state and first excited state of this system each involve a superposition of macroscopically distinct currents generated by the correlated motions of billions of electrons. Van der Wal *et al.* used microwave radiation to induce transitions between these two states. Remarkably, they found that the numerical predictions of quantum mechanics were satisfied in great detail even for quantum superpositions that involved the lowest possible energy states of the system. These results, along with those obtained by Friedman *et al.* (*2*) on transitions induced between superpositions of highly excited states of a similar SQUID system, represent a very important advance in the identification of the range of validity of quantum theory.

Does this end the debate? It certainly removes some of the lingering objections about the ability of quantum mechanics to calculate correctly the properties of systems with very large numbers of constituents. This is not just of philosophical interest. One intriguing practical application of macroscopic quantum phenomena may be in quantum computation. Quantum computers can potentially achieve massively parallel computation by manipulating all components of a superposition of states simultaneously. The van der Wal *et al.* (*1*) and Friedman *et al.* (*2*) experiments demonstrate that the technology exists to begin to implement the required structures as macroscopic superconducting circuitry and that quantum mechanics pro-

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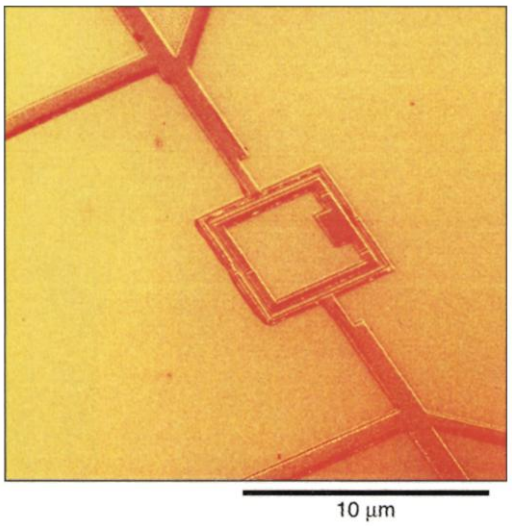

Toward quantum computation. Electron micrograph of the apparatus used by van der Wal *et al.* (*1*) to observe macroscopic quantum phenomena.

vides the necessary computational tools for the design and evaluation of the components.

Despite these impressive advances, however, the fundamental question of the inevitability of a quantum description of macroscopic phenomena has not yet been resolved. One outstanding issue is that of "quantum entanglement." The implications of this extraordinary phenomenon were first explored in a gedanken experiment in 1935 (*3*). Quantum entanglement occurs when two systems share a common quantum mechanical state. Such systems also share a common fate, even if they become physically quite separated. The results of a measurement performed on one will determine the results of future measurements on the second.

The development in time of an entangled state, or in fact any quantum state, occurs without substantial distortion only if the system is isolated from any measurement apparatus or from dissipative elements in the environment. Although van der Wal *et al.* do not address quantum entanglement as such, their careful evaluation of the effect of the measurement SQUID on the macroscopic quantum system is an important first step toward the realization of a macroscopic entangled state. Quantum entanglement lies at the heart of entanglement-based schemes for quantum cryptography (*4*) and quantum teleportation (*5*). It seems likely that the paradoxes of the past are about to become the technology of the future.

References

1. C. van der Wal *et al.*, *Science* **290**, 773 (2000).
2. J. R. Friedman *et al.*, *Nature* **406**, 43 (2000).
3. A. Einstein, B. Podolsky, N. Rosen, *Phys. Rev.* **47**, 777 (1935).
4. A. K. Ekert, *Phys. Rev. Lett.* **67**, 661 (1991).
5. C. H. Bennett *et al.*, *Phys. Rev. Lett.* **70**, 1895 (1993).

PERSPECTIVES: BIOMEDICINE

Combating Parkinson's Disease—Step Three

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About one million Americans suffer from Parkinson's disease (PD), and each year 50,000 individuals are diagnosed with this neurodegenerative disorder. Because early symptoms of PD may go unrecognized, perhaps as many as 5 to 10% of individuals over 60 years of age may have the illness. It has been known since the 1960s that loss of dopamine neurons in the nigrostriatal pathway of the brain results in the motor abnormalities characteristic of PD. The quest for improved PD treatments continues in incremental steps. Replacing dopamine neurotransmitter that is lost as the dopamine neurons degenerate (step 1) is the mainstay treatment for PD patients. The next steps—transplanting fetal nerve tissue to replace dopamine neurons that have been lost (step 2) and halting neuronal loss altogether with trophic factors (step 3)—are still in the early stages of clinical testing. A breakthrough for step 3 is now at hand with the report by Kordower *et al.* on page 767 of this issue (*1*). These investigators show that gene therapy with glial cell line–derived neurotrophic factor (GDNF) results in the rescue of dopamine neurons and reversal of motor deficits in a primate model of PD.

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Although known since ancient times, PD was not formally defined until 1817 when shaking palsy (paralysis agitans) was described by James Parkinson (*2*). For this the "saddest of diseases," Parkinson realized that "until we are better informed respecting the nature of this disease the employment of internal medicines is scarcely warrantable." Indeed, it was not until the 1950s that the first major breakthrough came with the discovery by Arvid Carlsson that dopamine is a neurotransmitter in its own right (for which he has won this year's Nobel Prize in Physiology or Medicine). Treatment with L-dopa (levodopa), the immediate precursor of dopamine, was shown to replenish brain dopamine levels and to counteract parkinson-like states induced in experimental animals (*3*). This led to the realization that patients with PD had severe dopamine loss in the basal ganglia (putamen and caudate) and to the development of L-dopa medication, still the mainstay treatment for PD.

Replacing lost dopamine neurons by grafting fetal nerve tissue (*4*, *5*) into the brains of PD patients has been efficacious in some patients (*6*) and remains an option for those with late-stage disease. The ultimate goal, however, is to reduce the need for cellular replacement strategies by halting the continuing loss of midbrain dopamine neurons and inducing sprouting of additional nerve fibers in those neurons that remain. Now known to be part of a family of four neurotrophic factors and to exert effects through a dual-receptor complex, GDNF is a potent stimulator of dopamine neuron growth in vitro (*7*). This trophic factor has also proven effective in a variety of PD animal models, including primates (*8*), thus raising hopes that it may be valuable clinically. However, delivery of GDNF to the correct target areas of the brain has proven problematic and was perhaps the reason for termination of a clinical trial in which GDNF was injected into the cerebrospinal fluid (thus reaching much of the central nervous system) of PD patients.

A principal difficulty with providing trophic support for neurons in the brain is that neurotrophic factors are proteins that do not easily cross the blood-brain barrier. Moreover, they typically exert a multitude of effects, often both inside and outside the nervous system, depending on the distribution of their receptors in different cells and tissues. Unlike hormones that are released into the circulation and reach receptors in remote target tissues, neurotrophic factors operate locally—they are taken up by nerve terminals and then are transported along axons to nerve cell bodies (see the figure). To benefit from the therapeutic effect of a neurotrophic factor while avoiding unwanted side effects, local delivery schemes—such as direct injection into brain target areas rather than systemic administration—work best.

To overcome the local delivery problem, Kordower and co-workers injected the GDNF gene carried in a lentiviral vector directly into the basal ganglia and substantia nigra of rhesus monkeys. The authors capitalized on the effectiveness of a new