Push-button entanglement

Rainer Blatt

Quantum mechanics allows matter to be prepared in a strangely correlated way called entanglement. In future, large numbers of entangled particles may be put to work in quantum computers and precise quantum measurements.

Quantum mechanics is almost a century old, yet the interpretation of its non-local character and its implications for measurement processes are still widely discussed. So the generation of a uniquely quantum-mechanical model system is of great interest for both fundamental and applied reasons. On page 256 of this issue, Sackett *et al.*[1], from the National Institute of Standards and Technology (NIST) in the United States, describe the quantum entanglement of four atoms. Before these experiments only two or three quantum particles had been entangled, but the latest work is not just an incremental achievement. The technique the authors use for the quantum preparation of matter is scalable to much larger numbers of entangled particles, so it may become a useful tool for quantum information processing and may help to improve the precision of large-scale quantum measurements.

The apparently strange predictions of quantum theory have led to the notion of 'paradoxes', which arise only when quantum systems are viewed with a classical eye. A famous example was given by Erwin Schrödinger, who devised the *Gedanken*, or thought, experiment in which a cat is concealed inside a box with a radioactive atom that may or may not decay in a certain time. If the decay of the atom is detected inside the box, a mechanism frees some prussic acid, which immediately kills the cat. The atom is a quantum object, so quantum mechanics applies and we can calculate the corresponding quantum state in the box. Because there is no contact between the cat and the outside world, then, according to quantum theory, the state inside the box must be described by a superposition of the cat being alive (atom not decayed) and the cat being dead (atom decayed). Only opening the box — that is, making a measurement in quantum-mechanical language — would reveal whether the cat is still alive or already dead.

In this *Gedanken* experiment we encounter one of the strange features of quantum theory: the fate of the cat is inextricably interwoven with the state of an atom. Because we don't know the state of the atom (after all, there is only a given probability for its decay), we can't know the cat's well-being. But if we know the cat is dead, we can be certain that the atom has decayed. This one-to-one correlation arises because the states are inextricably interwoven or 'entangled' — a phrase coined by Schrödinger[2–4]. Mathematically, the fact that the states 'know' of each other shows up in the wavefunction describing the entangled state, which cannot be expressed as a product of the wavefunctions of the constituent states.

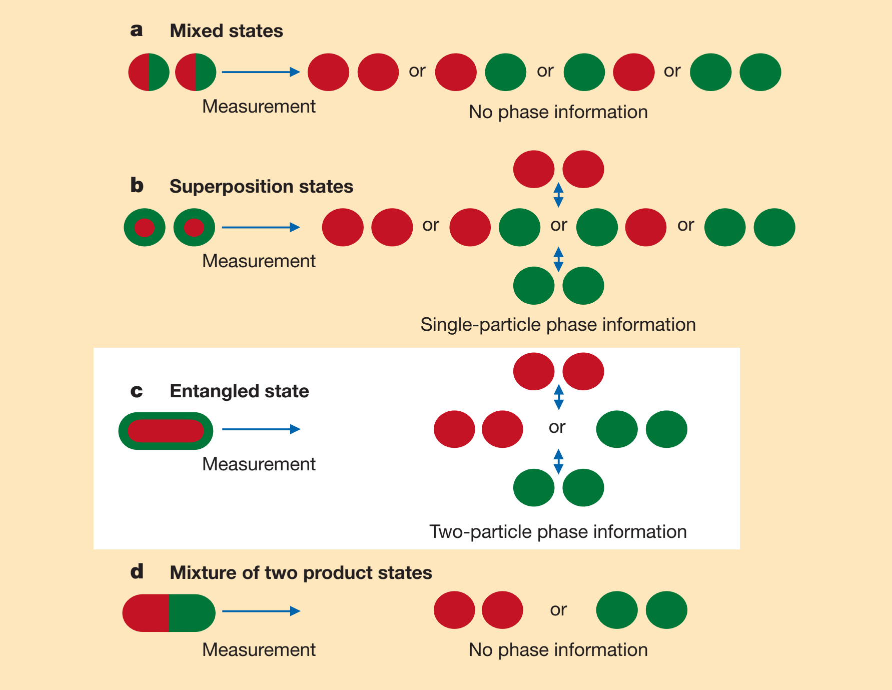

Figure 1 **Experiments with two particles, whose quantum states have two internal levels (green and red). A quantum state is completely described by its amplitude and phase. Vertical arrows indicate a coherent time evolution that reveals the phase information.** a, **The product of two mixed states: each state is populated with equal probability, so measuring the internal state yields, at any time, a random result out of four possibilities, but no phase information.** b, **The product of two superposition states: internal levels are superposed, for example by a coherent interaction, so measuring the state at certain times yields either two red or two green states with single-particle phase information or, at other times, a random result as in** a. c, **The entangled state: here two particles are entangled, for example by a coherent interaction, so measuring the state at certain times yields either two red or two green states or, at other times, a random result of either two green or two red states. This method provides two-particle phase information. The corresponding state with four-particle phase information was measured by Sackett *et al.*[1].** d, **A mixture of two product states: each of two product states is populated with equal probability, so measuring the state yields, at any time, a random result of either two green or two red states, with no phase information.**

Sackett *et al.*[1] report a new technique for entangling many particles at once and on demand — a crucial step towards quantum-state engineering and its application. Entangled states of particles have so far been prepared in only a few experiments. Pairs of photons can be entangled by parametric fluorescence in crystals[5], and atoms can be entangled with a microwave resonator[6]. Small Schrödinger-cat states of the spatial wavefunctions of a single trapped ion have been prepared[7] and the states of two ions in a trap can be entangled[8]. In all these experiments, entanglement is studied with two or three subsystems — that is, with photons, ions or an atom and a cavity. Only very recently, a three-particle entanglement (a so-called Greenberger–Horne–Zeilinger correlation) was observed and used to verify the predictions of quantum mechanics[9]. Experimentally, it is usually hard to prepare and observe such entangled states because any interaction with the environment represents a measurement and therefore immediately destroys the correlation (a process known as decoherence), in the same way as opening the box reveals the dead or alive cat.

In contrast, entangling states of many subsystems turns out to be a useful tool for quantum information processing. It has been shown that, by coherent manipulation of quantum states, quantum computers could solve certain problems much faster than conventional (classical) computers. This speed increase is directly linked to the fact that the register of a quantum computer can be prepared in a superposition of states, which are then processed in parallel. The creation of a 'universal' quantum computer becomes possible only if one can routinely prepare and handle entangled particles to serve as the storage sites of the quantum information. Moreover, the sensitivity of the entangled states (in particular, the large state prepared by Sackett *et al.*) with respect to interactions makes them a unique measuring tool. For example, we would like to measure the decoherence processes that cause errors in a quantum computation.

This is precisely why the new method for entangling many subsystems is an important step for the emerging field of quantum information processing. Sackett *et al.*[1] demonstrate for the first time an entanglement technique based on the ideas of Mølmer and Sørensen[10,11] that is applicable to any number of particles. In addition, this technique makes it possible to create maximally entangled states in a single step and on demand. Other entanglement experiments have relied on selection of suitable outcomes after the event of a random process (post-selection). In these cases, the probability of detecting the desired correlation drops exponentially with the number of entangled particles.

In an earlier experiment, the NIST group used a different technique to achieve 'surefire', or deterministic, entanglement of two particles by using a predetermined sequence of laser pulses[8]. In the new experiment the Mølmer–Sørensen procedure was followed, allowing them to entangle four particles with an appropriate single laser pulse. For quantum information processing, experiments with trapped and laser-cooled atoms are ultimately preferable to previous experiments with atoms and photons, in which entanglement is concluded from post-selection of randomly occurring coincidences rather than quantum state engineering.

Remember that these entangled atoms are a strangely correlated state of quantum matter: measurement of the state of a single atom (out of the four) is all that is needed to know the state of all the other atoms (Fig. 1). These would normally have to be found by other measurements if they were not entangled. Indeed, because the atoms 'know of each other', the outcome of the measurement contains the information of the entire system, not just of a subsystem. So entangled states will have many applications. They can be used to improve the precision of a measurement beyond the standard quantum limit, for example for time and frequency standards. They will serve as a tool to study decoherence processes and as a further check on the predictions of quantum theory. Eventually they will be used for quantum information processing, in which an exponential growth in the performance of algorithms, without a similar increase in resources, will rely on the degree of entanglement. Last, but not least, many-particle entanglement will become an essential tool for realistic error correction in quantum computers. Now that many-particle push-button entanglement can be achieved with comparatively little effort, it will pave the way for fundamental experiments and quantum state engineering. ■

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Plant pathology

Pathogen-driven forest diversity

Wim H. van der Putten

Why are some forests more heterogeneous than others in terms of the tree species they contain? This is the problem addressed on page 278 of this issue by Packer and Clay[1]. Unusually, they look into the diversity of a temperate (black cherry) forest (Fig. 1), but they find that a hypothesis about tropical-rainforest diversity proposed in the 1970s by Janzen[2] and Connell[3] is of relevance here, too.

Janzen[2] and Connell[3] proposed that the diversity of trees in tropical rainforests results from the presence of organisms — specifically, herbivores — that thrive on only one species of tree. The occurrence and density of such specialized herbivores, especially insects, correlates strongly with the presence of their host trees. These tree-specific herbivores eat both mature trees and saplings, and the saplings are more vulnerable to defoliation. So, the establishment of young trees is constrained in the vicinity of their parents, and only those seedlings that are dispersed to some distance from mature trees of the same species may survive[2,3]. However, as the herbivores are loyal to just one type of tree, other tree species may become established in the vicinity of the herbivore's target, generating tree species diversity.

This hypothesis has been widely tested, but few studies have looked at the part played by soil pathogens in controlling species richness[4], and most have dealt with tropical rainforests rather than temperate forests. Packer and Clay[1] address both of these issues. They show that, because a particular soil pathogen (a fungus of the genus *Pythium*) lives on the roots of mature black cherry (*Prunus serotina*) trees, the dispersal of black cherry seeds away from their parents is crucial for the establishment of saplings.


A. PACKER

Figure 1 **A black cherry (*Prunus serotina*) forest. Packer and Clay[1] propose that such forests owe their diversity in part to a cherry-tree-specific soil pathogen.**

Packer and Clay's test site was a forest near Bloomington, Indiana. They observed that black cherry seedlings underneath mature black cherry trees died soon after germination. Seeds that were dispersed some distance from the parents, however, survived and produced new trees. In theory, the death of the former seedlings could have been the result of overcrowding, a phenomenon known as density-dependent mortality. However, Packer and Clay found that distance from mature trees was a better predictor of mortality than tree seedling density.

The authors then carried out a study in the greenhouse, using soil taken from underneath black cherry trees or from some distance away. They sterilized half of each soil sample, transferred the different samples to pots, and planted each pot with one or three seedlings. Mortality was high in unsterilized soil from underneath the black cherry trees,