MOLECULAR QUANTUM TELEPORTATION

Beam me up Scotty

Although transporting a starship crewmember onto the surface of an alien planet is clearly science fiction, quantum state teleportation is not, and has been observed in various systems over the last few decades. Now, electron-spin teleportation has been observed in a carefully designed molecular system, paving the way for such behaviour to be tailored through molecular engineering.

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The concept of teleportation — the annihilation of matter in one point of space and time and its appearance in another — has been fodder for great works of science fiction for more than a century. It is no surprise that with the discovery of quantum mechanics in the first half of the 20th Century, and the advent of ultrafast computers and lasers in the latter half, scientists would begin to make serious efforts toward making quantum teleportation a reality. If successful, one would expect significant and rapid advances in the field of quantum information science (QIS), which encompasses many interesting sub-fields such as quantum computing, quantum sensing and quantum communications.

Teleportation experiments involving the quantum states of various forms of matter and photons have been reported in the past, but are somewhat rare. Even more scarce are experiments on molecular systems, which are attractive because chemists can, in theory, optimize the teleportation process through synthetic manipulation. Now, writing in *Nature Chemistry*, Wasielewski and colleagues describe[1] electron-spin-state teleportation from one end of an organic donor–acceptor–stable radical (D–A–R•) molecule to the other.

The concept of quantum teleportation met with initial resistance due to concerns, for example, about violating the Heisenberg uncertainty principle[2]. However, in 1993 Bennett and co-workers alleviated these concerns by proposing a system through which the quantum state of a particle was destroyed at one position and recreated at another (called a Bell measurement step)[3]. The research of Bennett and co-workers is considered to be the beginning of a realistic pathway to quantum computers. In 1997, Salikhov and co-workers suggested that a

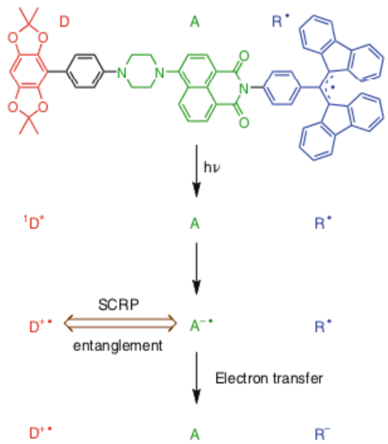

Fig. 1 | Structures and relevant processes for molecular quantum spin teleportation. After the electron spin state of R• is precisely established using a $\pi/2$ microwave pulse, optical excitation of D produces the first excited singlet state of D (^{1}D*). The ^{1}D*–A–R• system then undergoes charge separation (10 ps) to form a pure singlet entangled SCRP state D+•–A−•–R•. In the final step, an electron is transferred from A−• to R• (108 ps) destroying the unpaired spin state on R•. The Pauli exclusion principle dictates that the spin state of D+• matches that of R•.

fast chemical reaction, for example, electron transfer, could be an appropriate method for carrying out the teleportation of an electron spin state[4].

Electron spin is an attractive starting point for teleportation investigations because of the electron's small size and relativistic nature. Furthermore, chemists have provided many molecular frameworks from which species containing unpaired electrons (for example, radicals, radical ions and excited triplet states) are easily created in the laboratory — under precisely controlled conditions, in the solid, liquid or gas phase. A particularly useful technique to investigate the dynamics and reactivity of radicals is electron paramagnetic resonance (EPR) spectroscopy, which allows highly detailed information about the structure, motion and lifetime of a paramagnetic species to be obtained. The EPR experiment can be carried out in a pulsed mode, where spin angular momentum vectors can be precisely controlled with microwave pulses of certain widths over certain time scales.

Wasielewski and colleagues have combined synthetic methodology, laser excitation, chemical reactivity and pulsed EPR techniques to create very pure quantized electron spin states, whose energies and coherences can be manipulated and measured on the sub-microsecond time scale[1]. They describe a remarkable demonstration of successful quantum spin teleportation over a distance of ~2 nm, with high fidelity in three-dimensional space ('quantum spin tomography'). They take advantage of a structure called a 'spin-correlated radical pair' (SCRP)[5], created photochemically in a pure singlet-spin state. In the parlance of QIS, SCRPs are equivalent to entangled spin qubits. The two middle energy levels of an SCRP are a 'singlet' and 'triplet', defined by Bell as possible operational qubits in a quantum computer[6].

The overall process is depicted in Fig. 1. A molecule of the general structure donor–acceptor–stable radical (D–A–R•) is dissolved in an inert solvent, placed in the resonator of a pulsed EPR spectrometer, and cooled to 85 K to form a frozen glass with randomly oriented molecules. A $\pi/2$ microwave pulse prepares the spin state of R• as the starting point for an electron-spin-echo (ESE) experiment. Ultrafast optical excitation of D leads to a localized excited singlet state ^{1}D*–A–R•, which undergoes rapid charge transfer to create an entangled SCRP between D and A with essentially 100% singlet character (D+•–A−•–R•). Finally, an electron transfer reaction from A−• to R• leads to annihilation of the unpaired spin state on R• and a final state of D+•–A–R−. The Pauli exclusion principle is key to understanding how D•+ acquires the original spin state of R• — the electron transfer step is forbidden for A−•–R• triplet dyads, that is, only the statistically present singlet dyads (25%) undergo electron transfer and subsequent annihilation.

Figure 2 shows data from the ESE experiments that were used to observe teleportation within the system described in Fig. 1. The pulse sequences in Fig. 2a prepare the R• spin state, and then carry out ESE protocols to observe echoes from either R• or D+• (they are excited at different resonant frequencies). Different sequences are required to observe magnetization on the z versus the x and y axes (relative to the applied magnetic field B_0). When the echoes from R• and D+• are created along a particular axis, they are detected only along that axis and not along the other two. The fact that signals are detected along a specific axis after excitation along that same axis confirms a true quantum spin state teleportation event. Furthermore, analysis of these so-called 'quantum tomography' experiments enables the assessment of teleportation fidelities (reported as numbers between 0 and 1, where 1 represents complete fidelity between the destroyed and created quantum states). For the input state of R•, the fidelities are all greater than 0.99, and those for the teleported state of D+• are greater than 0.87. Fidelities above 0.67 are generally regarded as satisfactory for quantum computing operations[7].

The molecule has been carefully constructed for successful teleportation. First, the excitation of D and the initial charge separation event shown in Fig. 1 are both extremely fast, creating a pure singlet state SCRP. Second, in the charge separated state D+•–A−•–R•, the D+•–A−• dyad has a

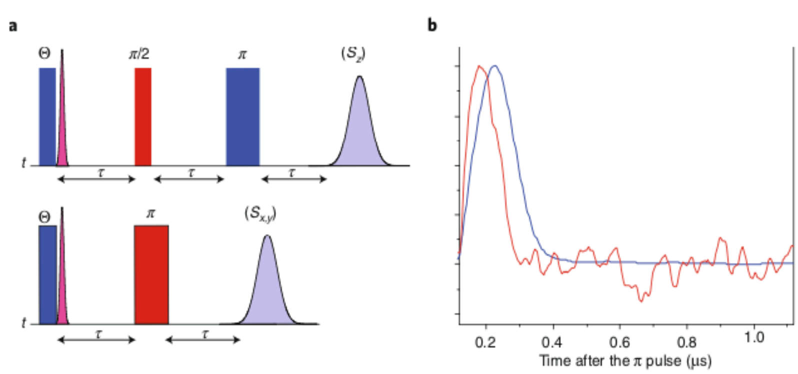

Fig. 2 | Experiments for observing quantum state teleportation. a, Pulsed microwave sequences used to detect magnetization (EPR signal intensity) $\langle S_i \rangle$ along a particular axis of the sample relative to an applied external magnetic field (defined as the z axis). The upper pulse sequence is used to probe $\langle S_z \rangle$ and the lower sequence to probe $\langle S_x \rangle$ and $\langle S_y \rangle$. **b**, An example of a quantum tomography experiment on the D–A–R• system that shows the nearly complete overlap of echoes from R• and D+•. This particular dataset is acquired using pulsed microwave excitation and detection along the y-axis. The blue curve is the spin echo resulting from probing the prepared state on R•, while the red curve is the spin echo resulting from teleporting the spin state of R• to D+•.

very large exchange interaction between its unpaired electrons. This effectively locks the $D^{+\bullet}$–$A^{-\bullet}$ dyad in the singlet state. These first two characteristics help to avoid side reactions from excited molecular triplet states or triplet SCRPs, and also prevent general loss of signal-to-noise in the teleportation step. Third, the electron transfer reaction from $A^{-\bullet}$ to $R^{\bullet}$ is exergonic. Also, at the operating frequency of the EPR spectrometer (34 GHz), the EPR spectrum of $R^{\bullet}$ and that of $D^{+\bullet}$ are well resolved, which means that the excitation pulses that lead to their respective echoes are isolated from each other. Finally, the last reaction of the cascade that takes $D^{+\bullet}$–A–R^{-} back to the starting compound D–A–$R^{\bullet}$ is very slow, guaranteeing that the only observed paramagnetic species at the observation time of >500 nanoseconds is $D^{+\bullet}$–A–R^{-}.

The work of Wasielewski and colleagues is important from many perspectives, of which two should be highlighted. First, the distance scale for teleportation accomplished here of 2 nm is exactly in line with the needs of nanoscale interconnects in information processing devices, and can be used as a guiding principle, as molecular QIS systems are assembled into larger meta-architectures for eventual device construction. Second, it firmly establishes the important role that chemistry plays in molecular design for a purpose. I predict that this paper will spawn a new wave of studies seeking to understand the effects of molecular structure on the types of properties studied by Wasielewski and colleagues, and how they can be manipulated for QIS applications. A lot of progress can be made in this field with experiments and theory, but the ability to systematically alter structures on almost an atom-by-atom basis adds a strong third dimension to a rapidly growing field. More sophisticated EPR detection methods of great utility to QIS are also likely to emerge from this work. ❐

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