

Perspective on exchange-coupled quantum-dot spin chains

Cite as: Appl. Phys. Lett. **119**, 030501 (2021); <https://doi.org/10.1063/5.0055908>

Submitted: 04 May 2021 • Accepted: 01 July 2021 • Published Online: 19 July 2021

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ABSTRACT

Electron spins in semiconductor quantum dots are a promising platform for quantum-information processing applications because their quantum phase coherence can persist for extremely long times. Nearest-neighbor electron spins naturally interact with each other via Heisenberg exchange coupling. Heisenberg exchange coupling results from the interplay of the electrostatic confinement potential together with the Pauli exclusion principle, which requires that no two electrons can have the same quantum number. Exchange coupling enables a host of useful capabilities, including the generation of different types of qubits, multi-qubit gates, ways to increase connectivity in systems of quantum-dot spin qubits, and routes to explore intriguing many-body phenomena.

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INTRODUCTION

Electrons are spin-1/2 fermions. As a result, the quantum-mechanical wavefunction of a collection of electrons must be antisymmetric under particle exchange. This antisymmetry has profound consequences, including effects associated with electronic band structure and quantum degeneracy pressure, which, respectively, make modern electronics and even solid matter possible. Another consequence of this antisymmetry is Heisenberg exchange coupling,^{1,2} which is a spin-spin interaction between electrons that results from the interplay of the electronic confinement potential, the Coulomb interaction, magnetic fields, and the Pauli exclusion principle. Exchange coupling underlies many important phenomena, like ferromagnetism.

Exchange coupling also has surprising and important consequences for the physics of few-electron systems. Semiconductor quantum dots are one of the most common ways to trap and manipulate individual electrons and thus offer a convenient set of tools to explore exchange coupling. In this Perspective, we will illustrate how to create and control exchange coupling in quantum-dot systems, how exchange can enable different types of spin qubits, how it can be harnessed for multi-qubit operations, including state transfer, and how it can enable studying the dynamics of interesting multi-spin systems. Despite directly coupling only nearest-neighbor spins, Heisenberg exchange coupling underlies a wide variety of interesting and useful tools for studying quantum information processing and the dynamics of interacting

spin systems. Although we restrict this Perspective to quantum dots, exchange coupling appears in many systems, including donor spins in semiconductors,³ cold atoms,⁴ and others.

After an introduction to exchange coupling in semiconductor quantum dots and a description of the different types of spin qubits and operations enabled by it, this Perspective will focus on recent work by the authors at the University of Rochester, which illustrates how exchange-coupled spin chains can transfer quantum information. Exchange coupling and related topics in semiconductor quantum dots are extremely active areas of research. Research groups at Delft University of Technology,^{5–9} ETH Zurich,^{10–13} Harvard University,^{14–17} HRL Laboratories,^{18–21} the Norwegian University of Science and Technology,^{22,23} Princeton University,^{24–27} National Research Council Canada,²⁸ Purdue University,^{29–31} RWTH Aachen University,^{32,33} Sandia National Laboratories,^{34,35} Seoul National University,^{36,37} the University at Buffalo,^{38–40} the University of California Los Angeles,⁴¹ University College London,^{42–44} the University of Copenhagen,^{45–48} Université Grenoble Alpes,^{49,50} the University of Konstanz,^{51–54} the University of Maryland,^{55,56} the University of Maryland Baltimore County,^{57–59} the University of New South Wales,^{60–62} Université de Sherbrooke,^{34,35} the University of Sydney,^{63–65} the University of Tokyo,^{66,67} the University of Wisconsin Madison,^{68–70} Virginia Tech,^{71–75} and other institutions are all involved in this exciting field. The interested reader is encouraged to consult the references herein for further information.

PHYSICAL IMPLEMENTATION OF EXCHANGE COUPLING

Gate-defined semiconductor quantum dots are created using a layered semiconductor containing a two-dimensional electron gas, such as a GaAs/AlGaAs heterostructure, Si/SiO₂ interface, or Si/SiGe quantum well [Fig. 1(a)]. Voltages applied to lithographically fabricated gates on the surface of the semiconductor laterally confine individual electrons [Fig. 1(b)].

Consider N electron spins in a linear chain of quantum dots, each containing a single electron. As a result of the wavefunction overlap between them, the Coulomb interaction, the details of the electrostatic confinement potential, and magnetic fields [Figs. 1(c) and 1(d)], a spin-spin interaction between electrons emerges,

$$H_{int} = \sum_{i=1}^{N-1} J_i \mathbf{S}_i \cdot \mathbf{S}_{i+1}. \quad (1)$$

Here, J_i is the exchange coupling strength between electrons i and $i+1$, and $\mathbf{S}_i = [S_i^x, S_i^y, S_i^z]$ is a vector of spin-1/2 operators. We have set Planck's constant $\hbar = 1$. The magnitude and sign of J_i depends on numerous factors, including the external magnetic field strength and the characteristics of the electronic confinement potential.^{71,76–78} Typically, $J_i \geq 0$ for electron spins in quantum dots although strong out-of-plane magnetic fields or neighboring multi-electron quantum dots can induce negative exchange.^{46,71} Theoretically predicting exchange couplings presents a challenge, and various levels of approximation are used to calculate it, including basic Fermi-Hubbard models, the Heitler-London approximation, the Hund-Mulliken approximation,^{56,76,77} and configuration-interaction calculations.⁷⁹

A straightforward calculation shows that the singlet $|S\rangle = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$ and the three triplets $|T_0\rangle = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle)$, $|T_+\rangle = |\uparrow\uparrow\rangle$, and $|T_-\rangle = |\downarrow\downarrow\rangle$ are eigenstates of the two-spin exchange operator. Moreover, the exchange coupling J indicates the

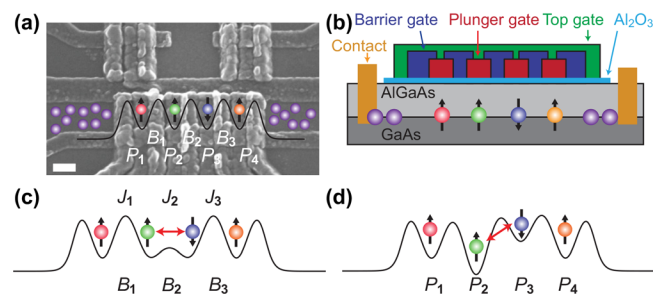


FIG. 1. (a) Scanning electron micrograph of a quadruple quantum dot in a GaAs/AlGaAs heterostructure. The positions and potential associated with the electrons are overlaid. Plunger gates P_i and barrier gates B_i can be used to induce exchange between electrons. Electron reservoirs (purple circles) are used to initialize the quadruple dot array. Two additional quantum dots above the main array are used for readout. The scale bar is 200 nm. (b) Schematic cross section of the device, showing the different metal and semiconductor layers used to create the device in panel (a). Further details about this device can be found in Ref. 29. Adapted with permission from Kandel *et al.*, Nature **573**, 553–557 (2019). Copyright 2019 Springer Nature. (c) Exchange coupling (red arrows) between two electrons may be induced by lowering the barrier between them. (d) Exchange coupling can also be induced by modulating the detuning, or difference between the electrochemical potentials of the two dots.

energy spacing between the singlet and triplet configurations of the two electrons.⁸⁰

Inducing exchange coupling between electron spins requires overlap between the electronic wavefunctions of neighboring quantum dots. Historically, exchange coupling has been most frequently tuned by oppositely controlling the chemical potentials, or the “detuning,” of double-quantum-dot structures [Fig. 1(d)].⁸¹ The basic idea of this approach is that by “tilting” one electron into another, one can controllably modulate the wavefunction overlap, and thus the exchange coupling between electrons. However, a recent generation of quantum-dot devices, with an “overlapping-gate” architecture,^{82–84} offers much tighter control of the quantum-dot confinement potential than traditional “open” quantum-dot architectures. In particular, overlapping gate architectures offer the ability to modulate specific parameters of the quantum-dot confinement potential, such as the barrier height or chemical potential, without significantly affecting other parameters, at least compared to open architectures. This precise control has made it possible to tune exchange couplings by directly controlling the barrier height between neighboring quantum dots [Fig. 1(b)].^{19,45} Lowering the barrier height shifts neighboring electrons closer toward each other,³⁰ and it may expand the quantum wavefunctions. Both effects will increase the size of the exchange coupling. A final technical advance, which has significantly increased the degree of control over exchange coupling, is the development of “virtual” gates,^{6,85–88} which enable independent adjustment of quantum-dot electrochemical potentials and barriers in multi-dot systems.

QUBITS AND QUANTUM GATES

Multi-spin qubits

Although the simplest possible spin qubit consists of an individual electron spin, the ability to manipulate exchange opens up the possibility to form different qubits out of multiple-spin states, as shown in Fig. 2. The potential advantage of such a qubit is the possibility of electrical spin-state control⁹⁰ and the potential to operate qubits in certain decoherence-free subspaces,⁹¹ which feature long-lived coherence even in the presence of specific kinds of environmental noise.

Perhaps the most common exchange-enabled multi-spin qubit is the singlet-triplet (S-T) qubit,^{81,89} formed from two electrons in a double quantum dot [Fig. 2(b)]. The S-T-qubit Hamiltonian is $H_{ST} = JS^z + \Delta B_z S^x$ in the $\{|S\rangle, |T^0\rangle\}$ subspace, where $|S\rangle = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$ and $|T^0\rangle = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle)$, and where ΔB_z is the difference in longitudinal magnetic fields between the dots, in units of frequency. This system occupies a decoherence-free subspace with respect to global magnetic fields that couple to the electron spins because neither the energy of the $|S\rangle$ nor the $|T_0\rangle$ state depends on the external magnetic field, in contrast to the energies of single-spin states. In addition, the S^z term in H_{ST} depends on electric fields, which are often easier to generate than pulsed magnetic fields in cryogenic environments. Singlet-triplet qubits, and variations thereof, have been the subject of significant theoretical and experimental research.^{14–16,33,35,61,70,81,92–98}

Following this line of thinking, three electrons in two or three quantum dots offer even more possibilities for high-performance spin qubits.⁵² Three electrons in a triple dot can create an “exchange-only” (EO) qubit^{18,20,28,90,99–101} [Fig. 2(c)]. In contrast to S-T qubits, which feature one electrical control axis, and one magnetic control axis (single-spin qubits require two magnetic control axes), EO qubits

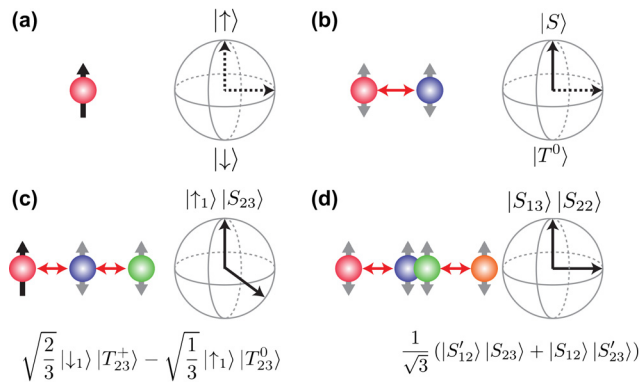


FIG. 2. Comparison between different types of spin qubits. In each panel, the number of spins involved in each qubit is shown. Solid lines on the Bloch sphere indicate exchange-based qubit control axes, and dashed arrows indicate magnetic control axes. (a) Single-spin qubit, requiring two magnetic control axes. (b) Singlet-triplet qubit, requiring one magnetic control axis.^{81,89} (c) Exchange-only qubit with two exchange-based control axes.⁹⁰ (d) Exchange-only qubit with four (or more electrons) with two orthogonal exchange-based control axes.^{22,23,53} Primed states involve excited levels, such as orbitals or valley states. In all panels, red arrows indicate exchange coupling. Gray vertical lines with two arrowheads indicate entangled spin states.

enable complete electrical control, and the two control axes correspond to exchange coupling between the two nearest-neighbor pairs of electrons in the triple dot. The eigenstates of a three-electron EO qubit usually consist of spin states with fixed total spin and triplet- or singlet-like states on one of the outer pairs of spins.^{20,90,99,100} Exchange-only qubits generally feature minimal static exchange couplings, and single-qubit gates are driven with baseband exchange pulses via barrier or detuning control.

Single-qubit gate times for EO qubits are determined by interdot exchange couplings, which are typically on the order of tens to hundreds of MHz. The hybrid qubit^{68,69} features similar spin states to the EO qubit, except that the three electrons reside in two quantum dots, instead of three. Thus, the single-qubit energy splittings are dominated by single-dot singlet-triplet energy spacings, which can be in the GHz range or higher, leading to the possibility of fast single-qubit operations.

Another variation of the EO qubit is the resonant exchange (RX) qubit, which also features three electrons in a triple quantum dot. In contrast to the EO qubit, the RX qubit features a large static exchange coupling, and single-qubit gates are driven by microwave modulation of the exchange couplings.^{47,102}

Extending this approach, qubits can also be formed with more than three electrons in three or more quantum dots, and exchange couplings provide complete control over the qubit dynamics.^{8,22,23,53} Such “singlet-only” qubits are predicted to offer a true decoherence-free subspace with respect to local magnetic fields that couple to the spin of the electrons, offering potentially improved coherence properties.

Initialization and readout

The exchange coupling between electrons describes the energy splitting between the singlet and triplet spin states. When both electrons reside in the same quantum dot, their wavefunctions overlap;

hence, their exchange coupling is maximized. The large singlet-triplet energy splitting of two electrons in the same dot leads to a phenomenon called the Pauli spin blockade, which is an essential tool for initialization and readout of multi-spin qubits.

To understand the Pauli spin blockade, consider the following heuristic picture of exchange coupling. If two electrons in separate quantum dots have a spin triplet configuration, which is symmetric under particle exchange, they must have an antisymmetric orbital configuration to guarantee the overall antisymmetry of the total wavefunction. Now, suppose that the electrochemical potential of the second dot is raised, such that the electron in that dot can tunnel into the first dot. When this tunneling occurs, the two electrons cannot both occupy the ground-state orbital of the first dot because the orbital wavefunction must be antisymmetric. Thus, this tunneling process remains energetically unfavorable until the electron can tunnel into an excited orbital of the first dot. Using a similar argument, one can see that if the two electrons have the spin singlet configuration, they can both occupy the ground state orbital of the first dot. Thus, for moderate offsets of the electrochemical potential, the spin singlet is the only possible combination of two electrons in a single quantum dot.

The Pauli spin blockade, which results from the exchange coupling of two electrons in a quantum dot, underlies many initialization and readout schemes for multi-spin qubits. For example, to initialize a S-T qubit, it suffices to couple a double quantum dot to an electrical reservoir in the presence of large exchange coupling. Because the singlet is the ground state, this process will cause preferential relaxation to the singlet. This process can be fast, on the order of tens of nanoseconds, and high fidelity.^{20,103,104}

Pauli spin blockade also enables fast readout of S-T qubits. After preparation and manipulation of an S-T qubit, the electrochemical potential of one dot can be raised, such that if the two electrons are in the spin singlet state, they can both tunnel into the other dot. If the two electrons are in the triplet state, they will remain Pauli blocked in separate dots. This spin-to-charge conversion can easily be monitored with an external charge detector, such as a quantum point contact, or an additional quantum dot.^{81,105} Low-noise amplifiers or radio frequency techniques can enable extremely rapid and high-fidelity readout.^{81,106–108}

Because EO and RX qubits involve singlet- and triplet-like states of groups of three electrons, Pauli-spin blockade techniques can also be used to prepare and read out their states. In the case of EO and RX qubits, adiabatic manipulation of the singlet- and triplet-like states into a single quantum dot suffices to prepare and project the qubit basis states, much like S-T qubits.^{100,102} Hybrid qubits generally involve singlet- and triplet-like states of electrons pairs in the same dot, so readout and initialization schemes typically exploit the spin-state dependence of the tunneling rate between the quantum dots and reservoirs.⁶⁸ For example, triplet-like states can relax to singlet-like states through a process involving an electron tunneling out of the dot, and another one tunneling back in. This brief change in occupation can be monitored with an external charge sensor, like a quantum point contact or quantum dot, as discussed above.

Single-qubit gates

Single-spin qubits require two magnetic fields for universal control: one static magnetic field, and one perpendicular, oscillating magnetic field. One notable advantage of exchange-enabled multi-spin

qubits is the possibility of electrical control. In fact, all of the multi-spin qubits discussed above rely on temporal control of exchange couplings via gate voltage pulses to implement single-qubit rotations. For S–T qubits and EO qubits, baseband exchange pulses, generated through detuning or barrier-gate pulses, are most frequently used to drive single-qubit rotations. High-fidelity single-qubit operations with baseband voltage pulses can be achieved although the relatively wide bandwidth required for precise baseband voltage pulses can present some challenges. However, careful pulse calibration can mitigate these issues.³³

In addition to time-varying exchange couplings, S–T qubits, which feature only two electrons, also require a magnetic control axis, in the form of a stabilized magnetic-field difference between the dots. This difference can result from multiple mechanisms, including a micromagnet,⁷⁰ dynamic nuclear polarization,¹⁰³ spin–orbit coupling,¹⁰⁹ or *g*-factor differences between the quantum dots.^{35,110}

Resonant-exchange and hybrid qubits are frequently driven with microwave voltage pulses. Although such pulses require attention to high-frequency wiring, the restricted bandwidth of these pulses compared to baseband pulses offers some advantages. Microwave-driven spin qubits are also particularly suitable for coupling to superconducting microwave resonators.^{10,21} Because they feature additional electrons compared to the S–T qubit, EO, RX, and hybrid qubits do not require magnetic control axes, although leakage to other states can depend on magnetic fields.

In addition to electric-field control, many exchange-enabled multi-spin qubits feature reduced sensitivity to magnetic fields, compared with single spins. This insensitivity to magnetic fields, however, comes at the expense of increased sensitivity to electric fields. Charge noise, as it is referred to in the quantum-dot spin qubit community, is a major obstacle to improved single- and multi-qubit gate fidelities.^{16,17,41,81,96,111–115} Carefully designed pulses^{116–118} and methods to minimize the sensitivity of the qubit to noise^{19,45,101} can mitigate charge noise to some degree, although understanding and controlling charge noise remains an intense area of research.

Another challenge for implementing quantum gates in Si spin qubits involves the valley splitting of the Si conduction band.¹¹⁹ In quantum wells or at interfaces, four of the six equivalent conduction-band minima are split off in energy. The remaining two valleys are split in energy by the microscopic details of the interfaces in the semiconductor. Frequently, the valley splitting is smaller than the orbital energy spacing in a quantum dot. As a result, valley splittings can place a limit on the maximum exchange couplings and singlet–triplet energy spacings in Si quantum dots,¹²⁰ posing multiple challenges for initialization, readout, and manipulation.¹²¹ In recent years, advances in the control of valley splittings and reliable fabrication of semiconductor wafers with large valley splittings have helped to solve this challenge.¹²²

A perennial difficulty for the creation of complex quantum-dot systems is the presence of static charged defects in the semiconductor that can hamper the creation of multiple-quantum-dot confinement potentials. Generally, GaAs/AlGaAs heterostructures feature extremely high mobility and correspondingly low levels of disorder, which promote easy tuning. In recent years, Si platforms have undergone significant advances that have enabled reliable fabrication and tuning of multiple quantum-dot structures, including the creation of dopant-free quantum wells,^{83,120} elimination of oxygen impurities,¹²³ and

improved control over valley splittings.¹²² In addition to material improvements, overlapping gate architectures^{82,83,124} and the concept of virtual gates^{6,85–88} have made it possible to create complex confinement potentials. Although tuning multiple-quantum-dot arrays in Si platforms is now generally routine, the smaller dot size in Si, due to its relatively large effective electron mass compared with GaAs, can pose additional challenges for fabrication. The large effective mass of Si quantum dots also means that barrier gates must be designed appropriately to achieve large enough tunneling and exchange coupling between electrons.¹²⁵

Multi-qubit gates

When two spins i and $i + 1$ evolve under exchange J_i for a time $T = \frac{1}{2J_i}$, the exchange coupling generates a SWAP gate. Evolution for $\frac{T}{2}$ produces a $\sqrt{\text{SWAP}}$ gate, which can entangle the two electrons. Together with single-qubit gates, a $\sqrt{\text{SWAP}}$ gate is sufficient for universal quantum computing.^{126–128} These facts illustrate on a basic level the potential of exchange coupling for quantum computing and information transfer and motivated initial proposals for quantum computing architectures based on semiconductor quantum dots.^{90,126,129}

In the presence of magnetic gradients between electrons, exchange coupling can enable other two-qubit gates for single spins, such as controlled-phase (CPhase) or controlled-not (CNOT) gates,^{54,130} both of which are also sufficient for universal quantum computing. In spin chains, magnetic gradients are routinely employed to provide single-spin addressability, making the realization of these gates a natural goal.^{24,60,131,132}

Exchange coupling also enables two-qubit gates between S–T qubits.^{32,63,133,134} This operation can be intuitively understood in the following picture. Although the S–T qubit eigenstates are commonly expressed as the set $\{|S\rangle, |T^0\rangle\}$, an alternative basis consists of the set $\{|\uparrow\downarrow\rangle, |\downarrow\uparrow\rangle\}$. Considering a chain of four electrons (two S–T qubits) with a non-zero exchange coupling between the second and third electrons, one can see that the state $|\uparrow\downarrow\rangle \otimes |\uparrow\downarrow\rangle$ will have a lower energy than the state $|\uparrow\downarrow\rangle \otimes |\downarrow\uparrow\rangle$, which leads to an effective Ising coupling between S–T qubits, although care must be taken to prevent leakage. Recently, evidence of this effective Ising coupling has been observed.¹³⁵

Exchange coupling between triple dots in various configurations can also lead to multi-qubit operations, including CNOT gates^{64,90,136,137} and CPhase gates.¹³⁸ Beyond two-qubit gates, exchange coupling can also enable three-qubit operations, such as a Toffoli gate²⁵ and entangling operations.³⁰

QUANTUM STATE TRANSFER

The capability of the Heisenberg interaction, which itself couples only nearest neighbor qubits, to implement operations spanning more than two qubits, is a recurring theme in this Perspective. In fact, exchange-coupled spin chains offer a host of different methods to transmit quantum states throughout spin chains.⁴³ Because quantum dot spin qubits naturally favor linear arrays, methods to transfer quantum states in spin chains are important for increasing connectivity in spin-based processors and error correction. In this section, we review recent experimental progress along various directions related to distributing quantum states in spin chains.

Coherent spin-state transfer via Heisenberg exchange

The simplest method to transfer quantum states with exchange coupling involves pulsed SWAP gates²⁹ [Fig. 3(a)]. Although straightforward in concept, this idea had evaded implementation in a system of more than two dots until recently. In Ref. 29, together with colleagues, we demonstrated this approach in a GaAs/AlGaAs quadruple dot device with overlapping gates (Fig. 4). We demonstrated transmission of single-spin eigenstates back and forth across the chain of four electrons through a sequence of SWAP operations [Figs. 4(b) and 4(c)]. Before and after each step, the two pairs of electrons were read out using spin-to-charge conversion techniques associated with Pauli spin blockade.^{14,81}

Any scheme for transmitting quantum states should ideally enable transferring unknown, arbitrary quantum states. To provide evidence that spin-state transfer via Heisenberg exchange satisfies this criterion, we transmitted one member of an entangled pair of electron spins using this approach.²⁹ In semiconductor quantum dots, entangled pairs of electrons can easily be created by initializing a quantum dot in the configuration where the ground state consists of two electrons in the dot.^{14,81} For most experimental conditions, the Pauli exclusion principle dictates that if both electrons occupy the ground-state orbital of that dot, they must have the spin singlet configuration $|S\rangle = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$. In a double quantum dot, this singlet can easily be separated into neighboring dots via tunneling.^{14,81}

In the presence of a magnetic field difference ΔB_z between the two dots, the singlet will evolve coherently to the unpolarized triplet state $|T^0\rangle = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle)$ and back with frequency $g\mu_B\Delta B_z$, where g is the electron g factor, and μ_B is the Bohr magneton.^{14,81} In GaAs/AlGaAs quantum dots, ΔB_z can arise from the contact hyperfine interaction between the electrons and the randomly polarized Ga and As nuclei, each of which has nuclear spin $I = 3/2$.¹³⁹ Together, the nuclear spins generate an effective random magnetic field at the location of each dot.^{14,81,94}

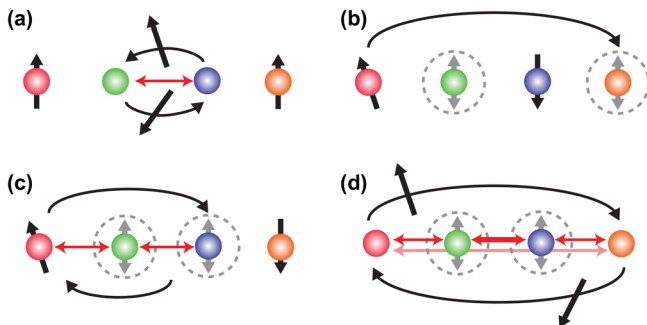


FIG. 3. Mechanisms of quantum state transfer enabled by Heisenberg exchange coupling. (a) Coherent spin-state transfer via Heisenberg exchange and pairwise SWAP gates, which transfer spin states between neighboring electrons. (b) Quantum teleportation, which involves separating an entangled pair of spins (2 and 4, gray). Spins 1 and 2 are measured in the Bell-state basis, which transfers the state of spin 1 to spin 4. (c) Adiabatic quantum state transfer, which involves modulating exchange couplings between spins 1–2 and 2–3 to transfer the single-spin state of 1–3, and the singlet state (gray) of spins 2–3 to 1–2. (d) Superexchange, which creates an effective, indirect exchange coupling between spins 1 and 4 (transparent red arrow), provided that spins 2 and 3 are configured as a singlet (gray) and provided the exchange coupling between spins 2–3 is stronger than the coupling between 1–2 and 3–4. In all panels, red arrows indicate exchange coupling. Curved black arrows indicate the transfer of spin states. Gray vertical lines with two arrowheads and dashed circles indicate entangled states.

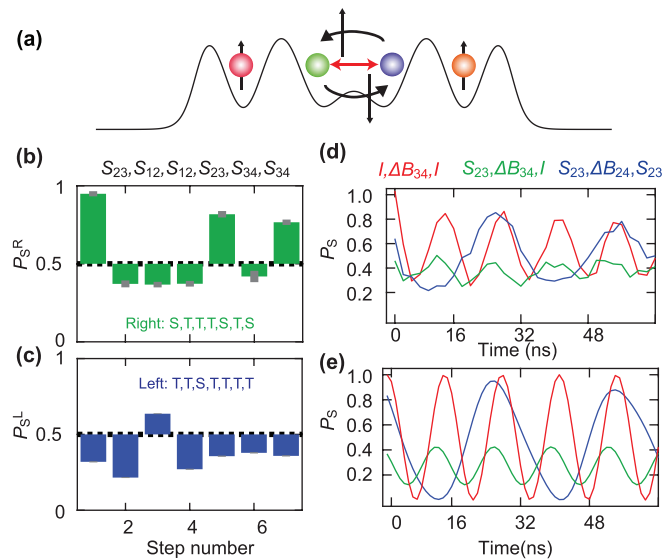


FIG. 4. Coherent spin-state transfer via Heisenberg exchange. (a) Lowering the barrier between two quantum dots induces exchange, which leads to a SWAP operation between spins. Concatenated SWAP pulses enable information transfer in spin chains. (b) Transfer of classical spin states. The experiment began with a spin down in dot 3. The sequence of SWAP operations was $S_{23}, S_{12}, S_{12}, S_{23}, S_{34}, S_{34}$. Here, S_{ij} means a SWAP operation between spin i and j . (b) Measured singlet-return probability of dots 3–4, the “right” pair. (c) Measured singlet-return probability of dots 1–2, the “left” pair. The data match the expected measurements, listed in the inset for each panel, confirming transfer of the classical state. (d) Prominent singlet–triplet oscillations (light blue) are observed after transferring an entangled pair to a distant location and back, indicating transfer of entangled states. The red and green lines are control measurements omitting one or both SWAP operations. (e) Theoretical simulations corresponding to (d). Panels (b)–(e) are adapted with permission from Kandel *et al.*, *Nature* **573**, 553–557 (2019). Copyright 2019 Springer Nature.

After swapping one member of the prepared entangled pair to a distant quantum dot using exchange-based SWAP pulses,²⁹ we allowed the pair to evolve for a variable length of time and then swapped the singlet back to its original location for measurement. We observed the characteristic singlet–triplet oscillations [Figs. 4(d) and 4(e)], consistent with our expectations that we transferred one member of the entangled pair to a distant location and back via SWAP gates.

Outlook

The ability to implement high-fidelity SWAP gates in linear chains of spin qubits is essential for various error correction schemes.^{140–142} We expect that such high-fidelity SWAP gates can now be achieved in Si spin qubits, where hyperfine fluctuations are reduced compared with GaAs spin qubits. Indeed, with the ability to perform SWAP gates, simple error-correction codes can potentially already be implemented with spin qubits.^{143,144}

Teleportation

The ability to coherently distribute qubit states is vital for quantum-information processing tasks, including quantum teleportation.¹⁴⁵ Teleportation involves distributing two members of an

entangled pair to two experimenters, Alice and Bob. To teleport an unknown qubit state to Bob, Alice should measure the unknown state together with her member of the entangled pair in the Bell-state basis. This measurement projects Bob's member of the entangled pair onto the unknown state up to a single-qubit rotation that depends on Alice's measurement. Creating the long-distance entangled pair had presented the most challenging obstacle to teleportation in quantum-dots^{98,146} and has been the focus of intense research.^{147–149} However, spin-state transfer via Heisenberg exchange²⁹ solved this challenge. In Ref. 150, we leveraged this advance to perform teleportation in quantum dots [Fig. 3(b)].

To implement teleportation in quantum-dots, we created an entangled pair of electrons via Pauli spin blockade in dots 3 and 4 of a four-dot array. We distributed the entangled pair via Heisenberg exchange to dots 2 and 4. To teleport a state from dot 1 to dot 4, we measured dots 1 and 2 together via Pauli spin blockade. When this measurement yields a singlet, which is a maximally entangled Bell-state, qubit 1 is expected to be teleported to qubit 4. This procedure is conditional because teleportation occurs only when the measurement of qubits 1–2 yields a singlet. (A triplet result from this measurement could be any one of the three other Bell states and thus does not provide enough information for complete teleportation.) The experiments of Ref. 150 demonstrated the essence of this teleportation procedure by teleporting a classical spin state.

To confirm that this teleportation procedure is coherent, we also performed entanglement swapping¹⁵¹ or teleportation of entangled states. To verify entanglement swapping, we prepared the system of four quantum dots in two pairs of entangled states: one pair in dots 1–2 and the other pair in dots 3–4. After a SWAP between qubits 2–3, such that the entangled states occupied dots 1–3 and 2–4, we measured dots 3–4 via Pauli spin blockade. On obtaining a singlet outcome, the spin state of dot 4 is teleported to dot 1. As a result of this measurement, the initial entanglement associated with dots 3–4 is teleported to dots 1–2. To verify proper teleportation of this entangled state, we allowed the singlet initially associated with dots 3–4 to evolve in its magnetic gradient for a variable time before teleportation. After teleportation, this oscillation was recovered on qubits 1–2.

Outlook

Looking ahead, experiments to demonstrate full, unconditional teleportation with quantum process tomography and feed forward to reconstruct the teleported states will result in a major advance for quantum-dot spin qubits. Unconditional teleportation requires a complete Bell-state measurement of the qubit to be teleported and one of the entangled pairs. A common technique involves measuring both qubits in their computational basis, following a disentangling operation.¹⁵² Usually, this measurement should occur faster than the qubit coherence time. This requirement poses a challenge for spins. Typical single-spin measurements via spin-selective tunneling usually take at minimum tens of microseconds to implement,¹⁵³ which is considerably longer than typical T_2^* times of several microseconds, even in isotopically pure Si.¹⁵⁴ Another challenge is that the fidelity of the Bell-state measurement directly impacts the teleportation fidelity. Thus, fast, high-fidelity measurements are essential for teleportation. A potential solution to this challenge exploits Pauli spin blockade and spin-to-charge conversion as discussed above. Typically, Pauli spin blockade is used to project a pair

of spins onto the singlet–triplet basis. However, in the presence of a magnetic gradient and adiabatic spin manipulation, Pauli spin blockade can effectively map a spin-zero product state (e.g., $|\uparrow\downarrow\rangle$) to a singlet, and all other spin states (e.g., $|\downarrow\downarrow\rangle$) to triplets, thus providing an effective mechanism to potentially measure single-spin states with high fidelity in short times.^{81,103} In principle, therefore, all of the elements to implement teleportation have now been demonstrated independently in Si spin qubits, including fast readout,¹⁵³ as well as high-fidelity single- and two-qubit gates.^{115,132,155}

Adiabatic quantum state transfer

Both of the quantum state transfer mechanisms discussed above rely on sequential exchange pulses. The ability to create multiple non-zero exchange couplings, discussed below, makes it possible to explore a variety of additional state transfer techniques. For instance, one exciting possibility is to adiabatically modulate exchange couplings in a spin chain. This procedure, sometimes called adiabatic quantum teleportation,¹⁵⁶ or adiabatic quantum state transfer (AQT), has the potential to enable high-fidelity state transfer without the strict pulse timing requirements associated with SWAP pulses. This process has been studied in great detail theoretically over the past decades,^{27,40,44,156–164} but has only recently been demonstrated experimentally. The key enabling advance was the development of the ability to create multiple, simultaneous non-zero exchange couplings in spin chains, as described in Ref. 30. The AQT process is closely related to stimulated Raman adiabatic passage, a time-honored technique from the optical physics community.¹⁶⁵

We implemented AQT in the same quadruple quantum-dot array discussed above¹⁶⁶ [Fig. 3(c)]. To transfer a spin eigenstate from dot 3 to dot 1, for example, we prepared a singlet in dots 1–2 by electron exchange with the reservoirs in the presence of large exchange coupling J_1 . Then, we decreased J_1 to zero and simultaneously increased J_2 . During this process, the spin state of dot 3 is transferred to dot 1, and the singlet state of dots 1–2 is transferred to dots 2–3. For spin eigenstates, the simulated fidelity of this process in GaAs quantum dots is about 0.95. The simulated fidelity for the transfer of arbitrary quantum states in GaAs quantum dots is lower because of the nuclear hyperfine noise. Crucially, the precise fidelity of this operation does not depend on the details of the pulses. This process can also be cascaded to enable long-distance transfer of both single-spin states and spin singlet states (Fig. 5). In principle, AQT is expected to be compatible with transferring arbitrary single-spin states, provided that the single-spin coherence time exceeds the AQT duration, which can be on the order of 100 ns. Such experiments could likely be realized in Si quantum dots, where spin coherence times are much longer than GaAs quantum dots. Although AQT and SWAP gates can both transfer single- and multi-qubit states, AQT has some potential advantages compared to SWAP gates. As discussed above, it is an adiabatic process, so the pulse timing requirements are not as strict, compared with SWAP gates. Adiabatic quantum state transfer can also transfer states over larger distances.

Outlook

The ability to implement AQT in semiconductor quantum dots opens up the possibility of adiabatic gate teleportation¹⁵⁶ and measurement-based quantum computation with spin qubits. Exciting future possibilities include exploring this effect in Si quantum dots,

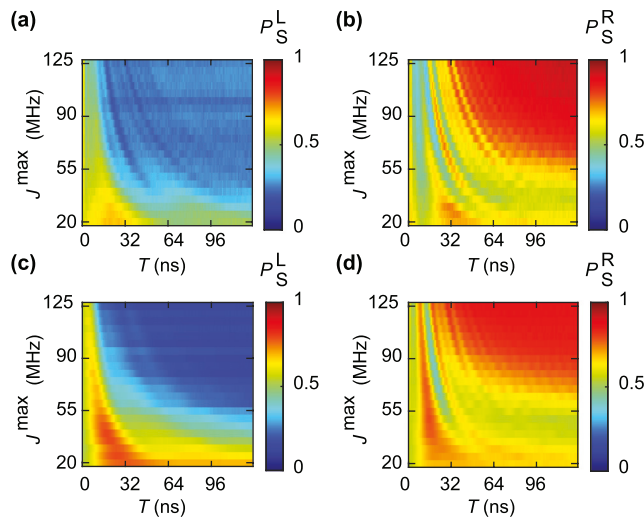


FIG. 5. Adiabatic quantum state transfer. (a) Measured left-side singlet return probability after a sequence of two AQT steps in a system of four quantum dots. Before the AQT sequence, the left pair has the singlet state, and the right pair is in a product state. The data are plotted vs maximum coupling strength $J^{\max}$ and ramp time T . (b) Measured right-side singlet return probability after the same sequence of two AQT steps. (c) and (d) Simulations corresponding to (a) and (b), respectively. In panels (b) and (d), the gradual increase in the singlet probability with increasing T for fixed $J^{\max}$ occurs because the process becomes increasingly adiabatic. The corresponding reduction in the singlet return probability with T in panels (a) and (c) occurs for the same reason. The non-monotonic behavior at fixed $J^{\max}$ is related to resonant state transfer. Kandel *et al.*, Nat. Commun. **12**, 2156 (2021). Authors, licensed under a Creative Commons Attribution (CC BY) license.

where it should be possible to transfer arbitrary single-qubit states and to explore various shortcuts to adiabaticity, which could enable fast, high-fidelity state transfer.^{40,167}

In addition to transferring single-spin states, AQT-like processes can also enable the transfer of multi-spin states,⁴⁴ such as singlet-triplet states. Indeed, the AQT process discussed above is already a simple version of this because the singlet state is transferred, in addition to the single-spin state. Another exciting possibility for future work is to transfer single-spin states over longer distances by working with entangled states spanning more than two qubits.⁴⁴ Important open questions for long-distance transfer involve the time required. In the absence of noise, the time required for high-fidelity AQT depends on the energy gaps between the multi-spin states in the system, with larger gaps allowing shorter times. The energy gaps depend on the exchange-coupling strengths and the number of spins. In the thermodynamic limit, the energy gap between the ground and first excited states decreases as $1/N$ where N is the total number of spins for a one-dimensional Heisenberg spin chain.^{168,169} Thus, all other things being equal, long distance AQT will require slower pulses for longer-distance transfer. Despite the expected increase in transfer time, however, the robust nature of the AQT process could confer some advantages for long-distance state transfer, compared with SWAP gates, for example.

Superexchange

On one hand, spin singlets are eigenstates of exchange coupling in semiconductor quantum dots and are thus “ordinary” eigenstates,

in some sense. However, on the other hand, spin singlets are maximally entangled pairs of electrons and are thus an essential resource for various quantum information processing tasks. One such task is “superexchange,” which is an effective coupling between distant spins,^{38,39,42,43,170–172} unlike conventional exchange, which only couples nearest-neighbor spins.

In semiconductor quantum dots, superexchange can occur in a variety of situations and generically involves an intermediate set of quantum dots that may be empty,⁵ singly,⁶² or multiply⁴⁸ occupied. One of the most frequently studied systems predicted to exhibit superexchange is a spin chain, consisting of two qubits weakly coupled to the ends of a strongly coupled spin chain.^{38,170,171} Although superexchange had previously been demonstrated in quantum dot systems with a single intermediate object (usually a single quantum dot, with zero, one, or many electrons), we leveraged the AQT process to implement superexchange between two end spins weakly coupled to a chain, which itself consisted of two spins.³¹

We implemented the following Hamiltonian in a system of four quantum dots:

$$H = j\mathbf{S}_1 \cdot \mathbf{S}_2 + J\mathbf{S}_2 \cdot \mathbf{S}_3 + j\mathbf{S}_3 \cdot \mathbf{S}_4. \quad (2)$$

When $j \ll J$, superexchange between spins 1 and 4 can occur when spins 2 and 3 have the singlet state, via virtual excitation to the polarized triplet configurations, and at an oscillation frequency of

$$J' = \frac{j^2}{2J} \left(1 + \frac{3j}{2J} \right), \quad (3)$$

up to third order in j [Fig. 3(d)]. If spins 2 and 3 have any of the triplet states, which are nominally degenerate, those spins will evolve in time at a frequency scale of j , and superexchange between the end spins cannot occur with a reasonable fidelity.

To realize this scenario, where the chain is prepared as a singlet, we harnessed the AQT process described above to transfer a spin singlet, originally prepared in one of the outer dots, to the interior of the array. We then implemented the exchange couplings discussed above and reversed the AQT process to read out both the end spins and the chain. We observed the expected dependence of the end-spin oscillation frequency on the exchange couplings, and we also verified that the expected superexchange behavior only occurs when the chain is configured as a singlet. Superexchange has long been predicted and studied in semiconductor quantum dots due to its potential for quantum information processing applications, and these results demonstrate its potential for long-distance spin-spin coupling.

Outlook

In the future, benchmarking these results in Si quantum dots, where high fidelity operations are expected to be possible, may provide additional tools for high-fidelity quantum computing. One obstacle to making use of superexchange for quantum-computing applications is that the mediator spins (spins 2 and 3 above) cannot be in an arbitrary state. In fact, they must be in the ground state of the Heisenberg Hamiltonian. However, as we have discussed above, Heisenberg spin chains enable several unique and advantageous ways to create, manipulate, and transfer spin singlets and their analogs in longer systems, potentially enabling the use of superexchange in quantum computing.

MULTI-SPIN DYNAMICS

Because they offer such precise control over electronic confinement potentials, quantum dots have long been noted for their potential to simulate many-body quantum systems of interest.^{6,8,173} Although many other quantum simulation platforms, including cold-atom and trapped-ion systems, have experienced significant progress, quantum simulation with semiconductor quantum dots provides unique opportunities to explore condensed matter quantum spin systems.

Controlling simultaneous interactions between multiple electrons, which is required for quantum simulation, remains challenging with quantum dots. In fact, independent and automated control of inter-dot tunnel couplings has been the focus of recent intense research.^{6,7,26,88,174,175} The most significant obstacle is the non-linear and non-local dependence of exchange couplings on the confinement gate voltages.^{6,30,175} We recently showed that the primary cause of this difficulty is the electronic wavefunction shifts that occur during exchange pulses (Fig. 6).³⁰ For example, during a typical barrier-gate pulse, the electrons on either side of the barrier move closer to or farther away from each other, depending on the sign of the voltage pulse. Electrostatic modeling of the potential during a barrier-gate pulse confirmed this picture.³⁰ In spite of this challenge, we showed that two models based on the Heitler–London formalism⁷⁸ could be used to predict the barrier-gate voltages given a set of desired exchange couplings. The model parameters, which describe how much the electrons move in response to voltage pulses, were found by measuring how each of the exchange couplings depend on all of the barrier gate voltages. These models are sufficient to enable the generation of coherent three- and four-spin exchange oscillations within a reasonably wide range of exchange-coupling values.³⁰ This approach is also extensible to longer arrays of quantum-dot spin qubits. Other approaches to

overcoming this challenge involve adjusting the detunings, instead of the barrier heights, of multiple pairs of dots.⁸

Looking ahead, we expect that model-based efforts will help guide the use of quantum-dot devices as they scale up in size and complexity. Moreover, the ability to generate multiple non-zero coherent exchange couplings opens up a wide array of phenomena to explore, including the AQT and superexchange protocols discussed above. In addition, this ability also opens up the possibility to explore quantum magnetism in many-body interacting spin systems, which is thought to underlie important phenomena, like high-temperature superconductivity, and which has been the focus of significant research in other simulation platforms, like cold atoms.¹⁷⁶ Specifically, quantum-dot spin qubits naturally enable realizing antiferromagnetic spin chains [Fig. 7(a)]. Antiferromagnetic spin chains are notable because their ground states are highly entangled. Recent experiments have already studied the ground states and dynamics of such a system in a system of four quantum dots.⁸

Disordered Heisenberg spin chains are also systems of great interest. Because of the naturally occurring nuclear hyperfine fluctuations, quantum-dot spin qubits enable a straightforward realization of this model. One interesting feature of disordered Heisenberg spin chains is the possibility of many-body localization, a phase of matter that seems to violate conventional assumptions about statistical mechanics. In a many-body localized system, despite the presence of interactions, disorder in the system prevents a subset of the system from fully entangling or thermalizing with the rest [Fig. 7(b)].¹⁷⁷ The prototypical system thought to exhibit many-body localization is the disordered, Heisenberg spin chain.¹⁷⁷ Although many experiments in other platforms have presented evidence for many-body localization,^{178–182} few have been able to reproduce this seminal model and instead involve longer-range interactions. Because quantum dots enable an exact realization of the disordered Heisenberg spin chain model, semiconductor quantum dots present an attractive platform to realize this phenomenon and related effects.¹⁸³

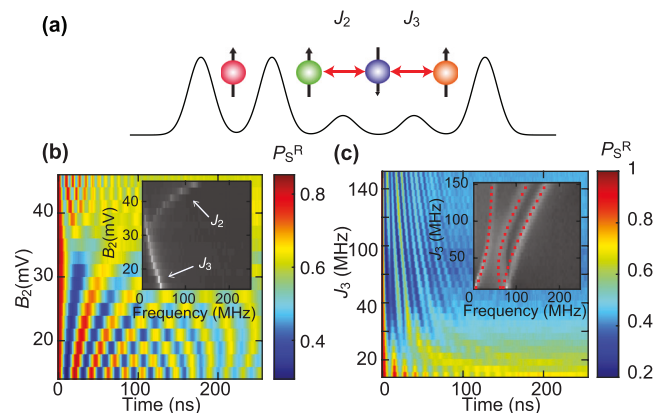


FIG. 6. Coherent multi-spin exchange. (a) Simultaneous exchange coupling is induced between spins 2, 3, and 4 by simultaneously lowering the tunnel barriers between dots 2–3 and 3–4. (b) Applying a positive voltage pulse to induce non-zero J_2 while $J_3 > 0$ dramatically reduces J_3 , which nearly vanishes before $J_2 > 0$. The inset shows the absolute value of the fast Fourier transform of each line. (c) Coherent three-spin exchange oscillations. For these data, J_2 was fixed at approximately 40 MHz, and J_3 was swept linearly from 10 to 150 MHz. The measured quantity is the singlet-return probability of spins 3–4. The inset shows the absolute value of the fast Fourier transform of each line, and the theoretical oscillation frequencies are shown in red dashed lines. Panels (b) and (c) adapted from Qiao *et al.*, Phys. Rev. X **10**, 031006 (2020). Authors, licensed under a Creative Commons Attribution (CC BY) license.

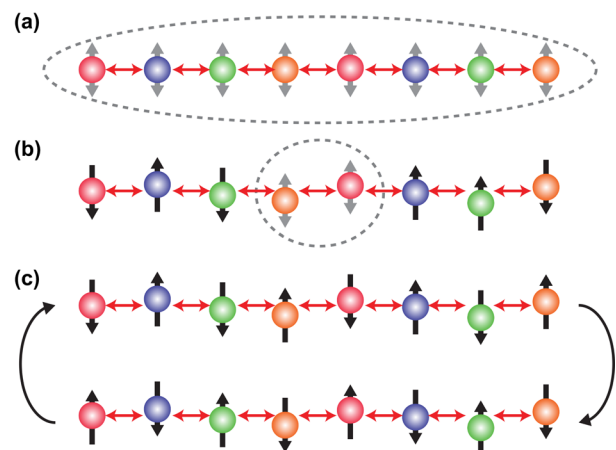


FIG. 7. Quantum simulation with electron spin qubits. (a) Heisenberg antiferromagnets, (b) many-body localization, and (c) time crystals. In all panels, red arrows indicate exchange coupling, and gray dashed circles, together with gray lines with two arrowheads, indicate entanglement. In panel (c), the curved black arrows emphasize that the time-crystal phase of matter stabilizes the periodic rotation of all spins, such that the spins alternate between the two configurations shown.

The time-crystal is another phase of matter that can occur in disordered spin chains.^{72,184–187} In a time-crystal, a parent non-thermalizing phase, such as a many-body localized phase, can stabilize a subharmonic response of the system to a periodic drive indefinitely [Fig. 7(c)]. The prototypical model for a time crystal is a disordered Ising spin chain. As in the case of many-body localization, the exact realization of this model has evaded implementation although evidence of phases related to time crystals has been observed in different systems.^{188–191} Although disordered Heisenberg spin chains do not enable creating a time crystal,⁷² it is possible to convert the Heisenberg interaction to an Ising form, through various mechanisms, including magnetic gradients^{73,130} and control pulses.⁷² Recent experimental work has suggested that exchange-coupled singlet–triplet qubits can also realize a form of discrete time-crystalline behavior.^{63,135} Although the practical applications of the many-body localized and time-crystal phases are not yet entirely clear, they may be useful in quantum information processing applications as ways to stabilize many-body quantum states.^{75,183}

Outlook

While semiconductor quantum dots offer significant control over nearly all aspects of the electrostatic potential and the parameters of spin Hamiltonians, the number of degrees of freedom that require experimental tuning is large, and extending the size of quantum-dot systems to the true many-body regime presents a formidable challenge. Some of the most promising approaches to overcome this challenge center on electrostatic simulations,³⁰ computer-automated tuning,^{7,88,192,193} and machine learning^{194–197} to control large systems of quantum dots. Ultimately, controlling systems of many quantum dots is also an essential challenge for large-scale quantum computing with spins. Thus, in view of the unique opportunities (ease of fabrication, exquisite controllability, natural realization of exchange coupling, etc.) afforded by electron spins for studying solid-state spin chains, together with the potential advantages (long coherence times, scalability, etc.) of quantum-dot spin qubits for quantum computing, this seems a worthwhile avenue of pursuit (Fig. 7).

FUTURE DIRECTIONS

Despite the significant advances in controlling and exploiting exchange coupling in quantum-dot spin chains in recent years, much exciting work remains to be done. On a fundamental level, continuing to understand, model, and predict exchange couplings will continue to drive forward progress in this field. In particular, understanding how to control multiple exchange couplings independently and simultaneously in larger spin chains for many-body quantum simulation or multi-qubit algorithms will create important and exciting opportunities and capabilities for both quantum computing and simulation.

The improvement of single- and multi-qubit gates driven by exchange remains an area of critical importance. In addition to the theoretical and model-based approaches mentioned above, methods to design and implement noise-resistant exchange pulses will likely become increasingly important as gate fidelities and device architectures mature to the level of error correction. On the device side, further work to understand and minimize effects like charge noise and valley splittings will also become increasingly important.

Different multi-spin qubit types are also yet to be experimentally investigated. In general, increasing the number of electrons in multi-spin qubits opens up pathways for reduced sensitivity to noise at the expense of more complex device designs or control. Whether or not these multi-spin qubits can offer an improvement for quantum computing applications remains to be seen, but they deserve to be explored. In fact, the great variety of potential qubits that can be formed from electrons in quantum dots is one of the unique features of the platform.

We have discussed multiple avenues for long-distance quantum state transfer in exchange-coupled spin chains. The experiments by the authors took place in GaAs/AlGaAs quantum dots in part due to the extremely high mobilities and low disorder possible in this platform, compared with Si platforms. However, GaAs/AlGaAs quantum dots feature pronounced hyperfine noise that cannot be eliminated through isotopic purification. In contrast, the most common natural isotope of Si has zero nuclear spin, and Si quantum dots feature significantly reduced hyperfine noise, compared with GaAs quantum dots. The implementation and exploration of these techniques in Si, including spin-state transfer via Heisenberg exchange, teleportation, adiabatic state transfer, and superexchange will be necessary to precisely quantify and benchmark the performance of these techniques and to explore how they might be useful for quantum computing experiments. In linear chains, methods to transfer quantum states between qubits are helpful for error correction, and it may be that these techniques can enable progress in this direction. In addition, the demonstration of unconditional teleportation in quantum-dot spin qubits will represent a milestone for this platform, signifying that many of the elements required for universal computing can be executed together with high fidelity in the same circuit.

CONCLUSION

In this Perspective, we have described multiple ways in which exchange coupling can enable different forms of qubits, gates, state-transfer operations, and the exploration of multi-spin dynamics. Heisenberg exchange coupling is an essential feature of electron spins in quantum dots, and it results from the interplay of the confinement potential and the Pauli exclusion principle. Although it directly couples only nearest-neighbors spins, exchange coupling has important effects for systems containing more than two spins, including long-distance quantum state-transfer. Although we have discussed many results in the context of GaAs/AlGaAs quantum dot spin qubits, they can easily be implemented in Si spin qubits. Si spin qubits offer the possibility of significantly enhanced electron spin coherence because the most common nuclear isotope of Si has zero nuclear spin. In the future, we expect that the development of these techniques, especially in Si qubits, will lead to significant advances in spin-based quantum information processing. These results also underscore how the fundamental yet counter-intuitive principles of quantum physics can enable exciting ways to manipulate spins for information processing and the exploration of condensed matter physics phenomena.

AUTHORS' CONTRIBUTIONS

Y.P.K. and H.Q. contributed equally to this work.

ACKNOWLEDGMENTS

This work was sponsored the Defense Advanced Research Projects Agency under Grant No. D18AC00025; the Army Research Office under Grant Nos. W911NF-16-1-0260 and W911NF-19-1-0167; the National Science Foundation under Grant Nos. DMR-1809343, DMR 2003287, and OMA 1936250; and the Office of Naval Research under Grant No. N00014-20-1-2424. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of the Army Research Office or the U.S. Government. The U.S. Government is authorized to reproduce and distribute reprints for Government purposes notwithstanding any copyright notation herein.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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