Coherent Holes in a Semiconductor Quantum Dot

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In 2002, the European Union–funded *Maculinea* management research project "MacMan" started and grew quickly into a multinational endeavor. Its aims were to elucidate the functional ecology and genetic structure of *Maculinea* systems across Europe, assess the suitability of *Maculinea* butterflies as indicators of biodiversity along a European transect, and develop standards for monitoring *Maculinea* butterflies as indicators and tools for grasslands and their management (*5*).

This collaboration saw major scientific breakthroughs in evolutionary and conservation biology (*1*, *2*, *6*–*10*). In particular, grazing prescriptions developed for *M. arion* habitats—where maintenance of short turf height is a key factor (*1*)—served as a blueprint for the development of mowing regimes for two wet grassland species within MacMan. However, because mowing creates less small-scale heterogeneity in vegetation than grazing does, the right conditions for these wetland *Maculinea* can only be achieved on the landscape scale (*11*). Survival chances are increased through the recently discovered biannual cycle of many *Maculinea* species; larvae stay in the ants' nests for nearly 2 years (*12*).

The application of ecological knowledge to practical conservation requires a high level of local acceptance. Socioeconomic studies have revealed a high willingness to pay by local inhabitants (*13*). This acceptance emanated from the fascinating ecology of these butterflies, in particular their ability to mimic ants (*8*) and their parasitic and carnivorous larval life in the nests of ants (*7*).

Population and niche models have now been made available and validated by 25 years of successful restoration of *M. arion* in the UK (*1*). This enables us to use *Maculinea* systems to explore future challenges, particularly to investigate and model the combined impacts of human-induced changes in climate (*14*) and habitat (*15*, *16*) on these species. The next studies should focus on their local adaptations, changing niches, and different needs across a gradient of local climates. These results should then feed into models to assess the impacts of land use, climate, and socioeconomic change under a range of future scenarios (*17*, *18*) in different European regions. The ultimate goal should be new predictions on the mitigation of harmful impacts of multiple drivers.

As Thomas *et al.* show, ideal microclimatic conditions for the host ants of the Large Blue are achieved through different vegetation heights under different macroclimates. These insights should be transferred into recommendations for habitat management. Higher vegetation under warmer climates might extend the survival chances of local populations, leaving more time for the insects to adapt to their local environment than is recognized in current paradigms (*15*). Furthermore, management may allow modest temperature change to be counteracted by either creating cooler niches or making them accessible through connectivity, thereby buffering expected impacts on the distribution of the butterflies under certain scenarios of future development. The effect might well be that the realized changes in distribution resemble those originally expected under a less severe scenario (*14*). All such models and derived conservation recommendations will, however, have to be tested against large-scale habitat manipulations.

The study by Thomas *et al.* shows that precise knowledge of an endangered species' ecological requirements under a given climate can enable conservationists to reverse current declines by restoring or creating optimum conditions. In insects, this alone may increase by two to three orders of magnitude the size and stability of current populations, as well as creating new ones in landscapes and generating more emigrants to migrate in the future to climatically suitable habitat patches.

Management that creates cooler microtopographies and later (cooler) successional stages in current grasslands should mitigate the impacts of climate warming in the short to medium term. Such mitigation may not provide long-term (>100 year) solutions. Nevertheless, the findings of Thomas *et al.* suggest that the period during which local genotypes may persist on their current sites can be doubled, increasing the chances that individuals will adapt to changed conditions or migrate to cooler regions.

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APPLIED PHYSICS

Coherent Holes in a Semiconductor Quantum Dot

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Quantum states of positive charge carriers may be more stable to information loss than those of electron-based systems.

Building a quantum computer requires finding a system with long-lived coherence—one in which the wave function of a quantum state maintains its phase over time. In solid-state implementations of quantum information processing, coherent states can be generated with electron spins, and semiconductor quantum dots are powerful platforms for preparing, controlling, and measuring electron spin coherence (*1*). However, interactions between the electron spin and its environment destroy the fragile coherence (*2*) and lead to a loss of information. On page 70 of this issue, Brunner *et al.* (*3*) address this problem by using "holes"—positive charge carriers that result from unfilled states in an electronic band. They demonstrate that one measure of coherence, the inhomogeneous dephasing time of the hole spin, is at least an order of magnitude longer than that for electron spins.

Two main decoherence mechanisms operate in semiconductor quantum dots: The

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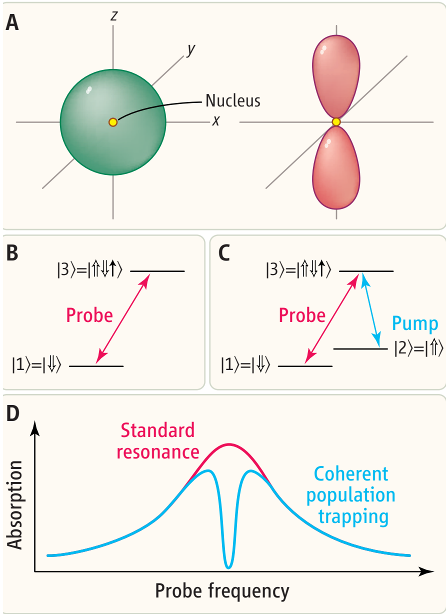
spin-orbit interaction couples the spin to its motion in the crystal, and the hyperfine interaction couples the electron spin to the spins of nuclei of the host material. Practical manipulations of electron spins are feasible on a subnanosecond time scale, and spin-orbit interactions are weak enough in semiconductor quantum dots to allow long spin relaxation times that exceed 1 s (*1*, *4*). However, the hyperfine interaction is a different matter. In a typical quantum dot, the electron spin interacts with roughly 1 million nuclei and experiences an effective fluctuating magnetic field on the order of 2 mT (*5*). This field limits the time-ensemble averaged coherence time, T_2^*, to roughly 10 ns (*2*). Spin echo and nuclear polarization methods that suppress the effects of the nuclei can extend the coherence time to greater than 1 μs, but correcting for the deleterious effects of the nuclear spins adds an additional layer of complexity to already challenging experiments (*2*, *6*).

The hyperfine interaction has three contributions. One term couples the electron's orbital angular momentum to the nuclear spin, and a second dipole-dipole term couples the electron and nuclear spins at a distance. Typically, the largest interaction is the contact term, in which the classically forbidden overlap of the electronic wave function with the atomic nucleus leads to a large scalar interaction. Several alternative solutions to hyperfine-induced decoherence have been proposed. Among the most promising are to use host materials with spin-0 nuclei, or to work with p-type semiconductors in which holes are the charge and spin carriers. A dramatic reduction in the contact term is expected because the hole's wave function vanishes at the nucleus (see the figure, panel A).

Brunner *et al.* measured the coherence of a single hole spin confined in ~10-nm-diameter InGaAs quantum dots grown on a GaAs substrate. They control the number of holes trapped in one quantum dot by tuning a gate voltage such that charge carriers tunnel out of the dot and into the substrate until only one hole remains (*7*). A static magnetic field causes the hole states to undergo Zeeman splitting into a lower-energy spin-down level $|1\rangle$ and a higher-energy spin-up level $|2\rangle$. Lasers linearly polarized in the plane of the substrate (the x and y directions) can excite transitions from the hole spin states to the positively charged exciton level $|3\rangle$, which consists of two holes in a singlet state and a spin-up electron (see the figure, panel B).

Electron-spin coherence times are typically determined by measuring the time decay of Rabi oscillations (periodic cycling between two Zeeman-split spin states) or by performing spin echo measurements that refocus the spin back to its original state. Brunner *et al.* instead use coherent population trapping (CPT), which has been widely studied in three-level atomic systems (*8*, *9*), in part because this method does not require high-speed control of optical pulse amplitudes. Recently, CPT has been applied to solid-state systems, including electrons confined in quantum dots (*10*, *11*).



Measuring hole-spin coherence. (**A**) Electrons in a quantum dot occupy s-orbitals (left) and interact strongly with the nuclei. Holes form p-orbitals (right) that vanish at the positions of the nuclei and reduce the contact hyperfine interaction that causes decoherence. (**B** to **D**) Adding a second laser to an absorption spectroscopy experiment allows measurement of hole-spin coherence times. (B) In a two-level system, the spin-down ground state $|1\rangle$ is excited by a probe laser to state $|3\rangle$. (C) A second pump laser adds excitations from spin-up state $|2\rangle$ and creates a three-level system. (D) The two-level system results in an absorption peak at resonance (red). The three-level system is quickly trapped in a coherent dark state that is a superposition of states $|1\rangle$ and $|2\rangle$. The dark state does not interact with the lasers and results in a dip in absorption (blue) whose depth is determined by the hole-spin coherence time T_2^*.

In standard laser spectroscopy, two-energy-level systems are probed by measuring the laser absorption or transmission as a function of laser frequency. In the Brunner *et al.* experiment, temporarily ignoring state $|2\rangle$, the absorption of a y-polarized probe laser would peak around energies corresponding to the $|1\rangle$ to $|3\rangle$ transition (see the figure, panels B and D). The peak width is then set by the radiative lifetime of state $|3\rangle$.

In the CPT experiments, a pump laser is added to excite the $|2\rangle$ to $|3\rangle$ transition (see the figure, panel C). When the pump and probe lasers are tuned to energies that match their respective transitions, a coherent superposition of states $|1\rangle$ and $|2\rangle$ called the "dark state" is created rapidly once state $|3\rangle$ decays. The destructive interference of the two laser beams used for excitation prevents excitation of the dark state. Pumping of the bright superposition states into $|3\rangle$ followed by incoherent decay eventually drives the system into the dark state. As the probe laser is tuned through resonance, a dip in absorption profile results because the holes are quickly trapped in the dark state and cannot absorb light (see the figure, panel D).

The depth of the absorption dip is a sensitive measure of coherence (*12*); decoherence converts the dark state back to a bright emissive state and provides an observable limit of CPT. Because of the long measurement times, the measured hole spin coherence time is an ensemble-averaged or T_2^* value; averaging over many measurements limits the visibility of the destructive interference in the decay curves. Through rate equation modeling of the absorption dip, Brunner *et al.* find that T_2^* is almost certainly greater than 100 ns and has a 40% likelihood of exceeding 1 μs.

More investigation is required to determine what mechanism limits T_2^* and to determine the inherent coherence time T_2. Recent theoretical results suggest that dipole-dipole hyperfine interactions may still lead to appreciable decoherence (*13*). Even so, with $T_2^* \geq 100$ ns, hole spins remain coherent an order of magnitude longer than electron spins, indicating that nuclear interactions might indeed have a weaker effect on holes. The next step for quantum information processing will be to demonstrate time-resolved coherent control of an initially prepared hole spin state. Recent experiments demonstrating picosecond optical control of electron spin suggest that similar experiments on hole spins may be just around the corner (*14*).

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