PNAS COMMENTARY

Diamond spins making waves again

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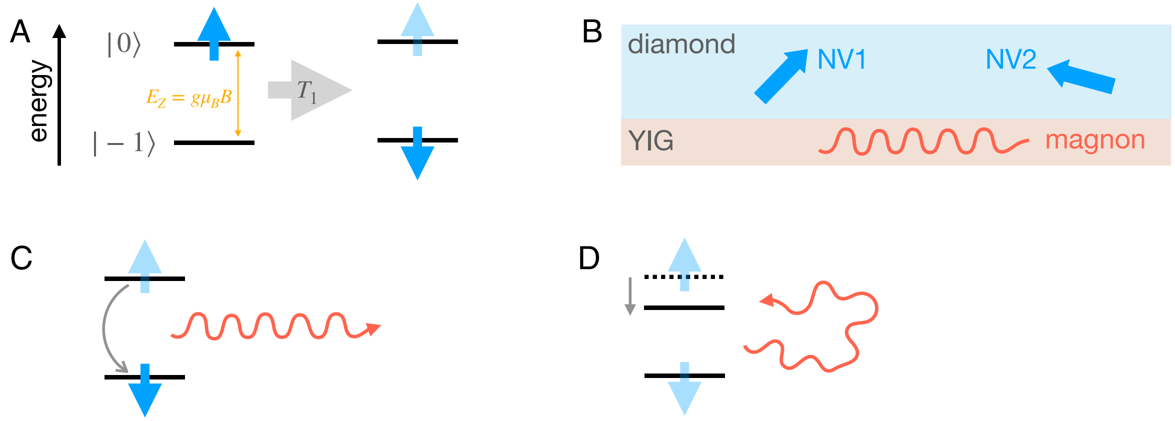

Fig. 1. (*A*) Spin relaxation: The two electronic states (shown as energy levels) |0> and |−1> with different spin quantum numbers (here $m_s = 0$ and $m_s = -1$) are split by the Zeeman energy $E_Z = g\mu_B B$ in a magnetic field *B* where *g* denotes the electron Lande g-factor and μ_B is the Bohr magneton. When prepared in the energetically higher $m_s = 0$ state, the system relaxes after a characteristic spin relaxation time T_1 to the energetically lower $m_s = -1$. Although the spin of the NV$^-$ defect amounts to S = 1, the blue arrows make reference to spin-1/2 notation which can be used for the subspace spanned by |0> and |−1>. (*B*) Schematic setup studied by Fukami et al. (3). A diamond slab containing the NV spins is placed on a magnetic insulator (YIG) that hosts spin wave excitations (magnons). Magnons can influence the NV spins by means of their magnetic field and therefore mediate coupling between NV spins. (*C*) Spin relaxation process by magnon emission. Absorption of magnons can also lead to spin relaxation toward the thermal equilibrium. (*D*) Self-energy (Lamb shift) due to magnon emission and reabsorption (or vice versa). The self-energy and relaxation rate are linked by the Kramers–Kronig relation.

Why has the nitrogen-vacancy (NV) center—an atomically small impurity occurring in diamond—received so much attention in the last two decades? It's not because it imparts a beautiful pink color to diamonds, but for the most part because it features a quantum mechanical spin, a tiny magnetic moment that can exist in discrete quantum states and that can be addressed and coherently controlled with light or with microwave radiation (1, 2). The diamond crystal surrounding these NV center spins is a wide-gap semiconductor and happens to be an almost perfect shield against various external perturbations affecting the NV spin. The isolation of NV centers benefits the quantum-mechanical coherence of the NV spins, i.e., the preservation of superpositions between the discrete states with a stable phase relation. It turns out that quantum coherence of the NV spin survives for fairly long times even at ambient conditions, i.e., at room temperature, while other solid-state qubits need to be refrigerated to about one Kelvin (−272 °C or −458°F) or below to prevent their coherence from being severely degraded by thermal fluctuations. In short, the NV spin has some of the ideal properties one can wish for in a qubit. Quantum bits, or qubits for short, are the elementary information units that make up the memory of a quantum computer and other quantum devices. That is to say, the NV spin has ideal properties as a quantum memory. When it comes to performing computations, qubits are supposed to interact with each other, and this is where the good isolation of qubits from their surroundings gets in the way. Writing in PNAS, Masaya Fukami and coworkers present evidence for a novel coupling mechanism that has the potential to overcome this limitation (3).

The trick is to couple the quantum system possessing one desired property (long coherence) with another quantum system that adds the lacking property (strong and long-distance coupling between qubits). Such combinations of qualitatively different quantum systems are sometimes referred to as hybrid quantum systems (HQS) (4, 5). In the past, the NV center and other defects in diamond (6–8) and silicon carbide (SiC) (9) have been coupled to light quanta (photons) that can carry quantum information over long distances with very small losses. Coupling defects in diamond or SiC to a photonic network can enable distributed quantum computing and quantum communication (10, 11). However, coupling NV centers to photons coherently is challenging because, (i) due to the small size of the NV center and other defects, their electric dipole is fairly small which implies a rather small coupling to photons, and (ii) the emission occurs predominantly into phonon sidebands and not into the zero-phonon line (ZPL) where quantum coherence would be preserved. There are a number of ways to address these

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challenges, among them, the use of alternative defects such as the silicon-vacancy center in diamond that predominantly emit into the ZPL (6, 7). An alternative would be to use spin waves in a ferromagnet, also known as magnons, to couple distant spin qubits (12). Fukami et al. in fact propose to use such magnons to couple two NV spins at a distance, and they experimentally determine the coupling strength between the NV spin and the magnons. To be more precise, in this case a ferrimagnet is used, consisting of two (or more) sublattices with aligned spins that can partially but not fully compensate each other. Here, the magnetic insulator yttrium iron garnet (YIG) is used because spin waves have very low losses in YIG, which means that magnons are very long-lived.

In the future, as Fukami et al. impressively demonstrate, magnons may well end up as one of the leading mediators of long-range coupling between solid-state spin qubits.

In their experiment, Fukami et al. determine the strength of the magnon-mediated interaction between NV spins indirectly. A diamond slab containing the NV centers is placed on top of a YIG film in which magnetostatic surface spin waves (MSSW) can be excited in a controlled way (13, 14) (Fig. 1*B*). Using optically detected magnetic resonance, a firmly established technique to probe NV spin dynamics, the relaxation time T_1 of the NV spin is measured as a function of the applied magnetic field in the absence and in the presence of the spin waves. In a magnetic field, the energy of different spin states is split by the Zeeman effect; the spin relaxation time (at low temperature) indicates how long it takes until the NV center undergoes a transition from a spin state with a higher energy to a spin state with a lower energy (Fig. 1*A*). More precisely, since the NV center is a quantum object, $1/T_1$ defines the exponential decay rate of the probability of the NV to be in its excited state. Often, spin relaxation in solids at low temperature occurs via the spontaneous emission of phonons or quantized lattice vibrations. Importantly, in the experiment reported by Fukami et al., the emission and absorption of magnons contributes to the spin relaxation rate (Fig. 1*C*). The change in the relaxation rate $1/T_1$ is measured as a function of the magnetic field and is found to reach a maximum at precisely the field where the Zeeman energy splitting matches one of the MSSW modes, confirming the magnonic origin of the extra contribution. A neat trick is the use of the Kramers–Kronig relation which fundamentally relates the dissipative and non-dissipative (reactive) part of any causal response function. In the case of NV centers coupled to magnons, the Kramers–Kronig relation can be used to convert the energy-dependent relaxation rate (dissipation) into the magnon-induced self-energy or Lamb shift (Fig. 1*D*). This self-energy in turn lends itself to the calculation of the expected magnon-mediated coupling between NV spins. The resulting coupling in the range of several Hertz is still modest compared to relaxation and decoherence rates in the Megahertz range, but it exceeds the expected dipolar interaction between NV spins. Moreover, there is still some way to improve this by optimizing the working regime, e.g., by reducing the distance between the NV center and the YIG film.

The NV center in diamond is not the only solid-state qubit that faces challenges regarding qubit–qubit connectivity. Coupling electron or hole spin qubits in semiconductor quantum dots, e.g., is highly efficient and reliable via the exchange coupling, leading to high-fidelity quantum gates between adjacent spin qubits. However, universal quantum computation and quantum error correction also require the availability of coupling mechanisms between non-adjacent and even far-remote qubits. One possibility here would be spin shuttling on a chip (15–18), while other options rely on HQS approaches. Among those, the coupling of semiconducting spin qubits to superconducting microwave resonators has progressed most (19), recently achieving the milestone demonstration of a non-local quantum gate in the time domain (20). In the future, as Fukami et al. impressively demonstrate, magnons may well end up as one of the leading mediators of long-range coupling between solid-state spin qubits.

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