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Toward Programmable Quantum Processors Based on Spin Qubits with Mechanically Mediated Interactions and Transport

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Solid-state spin qubits are promising candidates for quantum information processing, but controlled interactions and entanglement in large, multiqubit systems are currently difficult to achieve. We describe a method for programmable control of multiqubit spin systems, in which individual nitrogen-vacancy (NV) centers in diamond nanopillars are coupled to magnetically functionalized silicon nitride mechanical resonators in a scanning probe configuration. Qubits can be entangled via interactions with nanomechanical resonators while programmable connectivity is realized via mechanical transport of qubits in nanopillars. To demonstrate the feasibility of this approach, we characterize both the mechanical properties and the magnetic field gradients around the micromagnet placed on the nanobeam resonator. We demonstrate coherent manipulation of a spin qubit in the proximity of a transported micromagnet by utilizing nuclear spin memory and use the NV center to detect the time-varying magnetic field from the oscillating micromagnet, extracting a spin-mechanical coupling of 7.7(9) Hz. With realistic improvements, the high-cooperativity regime can be reached, offering a new avenue toward scalable quantum information processing with spin qubits.

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Introduction.—Isolated spin defects in the solid state, such as nitrogen-vacancy (NV) centers in diamond, have long been considered as promising candidates for quantum information processing, owing to their extended coherence times even at elevated temperatures [1–5]. While small spin registers have been realized using coupled electronic and nuclear spins [6–8], such demonstrations rely on magnetic dipole-dipole interactions, which limit the distance between spins to tens of nanometers. The short-range nature of these interactions and imprecision of defect fabrication at these length scales make it challenging to control systems containing large arrays of spin qubits.

Several approaches are currently being explored to address this challenge, including long-range entanglement based on photonic [9,10] and mechanical systems [11,12]. In particular, nanomechanical resonators have been proposed as a mesoscopic interface between distant and otherwise isolated spin qubits. Such a hybrid quantum system can be realized by combining electronic spins with magnetically functionalized mechanical resonators [13–24]. Mechanical resonators can be engineered to have very high quality factors with flexible, compact geometric realizations and feature low crosstalk relative to their electromagnetic counterparts [25]. Using mechanical modes as a quantum transducer, distant spin qubits can be entangled deterministically, even when the mechanical mode is in a thermal, highly excited state [11,26,27]. Furthermore, spin qubits can be used to cool the mechanical resonator to its ground state [28,29] and subsequently prepare non-Gaussian states of motion [30]. Despite these intriguing proposals, realizing the necessary strong coupling between mechanical systems and individual spin qubits is a challenging task, requiring deterministic positioning of spin qubits in close proximity to magnetized mechanical resonators. Moreover, even though transducers extend the spin-spin interaction range, the system connectivity remains local, limiting its programmability and scalability.

In this Letter, we introduce a novel platform for realizing programmable interactions between distant spin qubits. The key idea of our architecture is illustrated in Fig. 1(a). In our approach, individual NV centers in diamond nanopillars are coupled to silicon nitride nanobeam mechanical resonators in a scanning probe geometry. A micromagnet attached to the nanobeam provides the magnetic field gradient for the spin-mechanical coupling. Pairs of NV centers can be moved close to a mechanical resonator which, in turn, mediates entanglement between the former [26,27]. For example, following the proposal in [27], the NV centers can be used to conditionally excite the motion

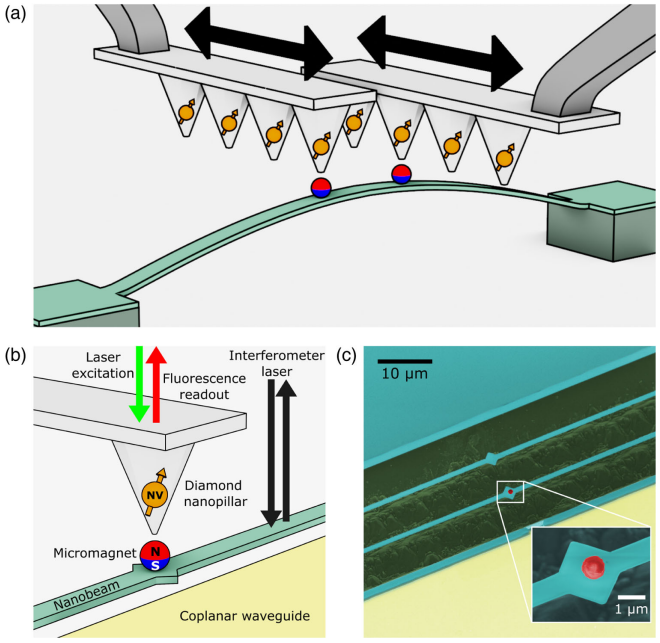

FIG. 1. (a) Conceptual diagram for programmable interactions within arrays of nanopillars containing spin qubits. Spin qubits (orange) can be micromanipulated (black arrows) to interact with a common mechanical mode of a magnetically functionalized resonator (turquoise), enabling mechanically mediated spin-spin interactions. (b) Our current experimental realization: a diamond nanopillar containing a single NV center at its tip is positioned above an NdFeB spherical micromagnet at the center of a doubly clamped silicon nitride nanobeam. A coplanar waveguide on the same chip facilitates coherent microwave control of the NV center's electronic spin. The chip is mounted on a three-axis nanopositioner stack, while the diamond nanopillar is kept fixed. (c) False-color scanning electron microscope image of the nanobeam (turquoise lines, two shown) with a micromagnet (red sphere) placed on a pad at the antinode of motion. Gold area at the bottom of the image is the coplanar waveguide. Inset: enlarged image of the micromagnet.

of the mechanical resonator, which is then measured to project the spins into an entangled state, even if the spins are across disparate teeth in each nanopillar comb.

Ultrahigh quality factors $Q > 10^9$ have been demonstrated in silicon nitride mechanical resonators through a combination of techniques such as soft clamping, dissipation dilution, and strain engineering [31–35]. At the same time, the nanoscale footprint of the diamond nanopillar enables small separations between the NV center and the micromagnet [36,37], providing access to high magnetic field gradients required for large spin-mechanical coupling. Remarkably, spin qubits confined in nanopillars can be moved mechanically in and out of the near field of the magnetized resonators. Moreover, they can be transported across relatively long (10–100 μm) distances, enabling nonlocal connectivity between distant qubits [38–43]. Further improvements in coherence time can be obtained by making use of a nuclear spin quantum memory. Since the latter is less sensitive to magnetic fields, such storage can be used for long-distance qubit transport even in the presence of proximal magnetic gradients, enabling reconfigurable quantum processing architecture similar to that demonstrated recently for neutral atom array qubits [38].

Experimental setup and static magnetic field characterization.—Our experimental platform consists of a scanning probe setup, where a (100)-diamond nanopillar containing a single NV center is positioned near a micromagnet placed at the center of the nanobeam [Figs. 1(b) and 1(c)]. In addition to improving the optical collection efficiency, the nanopillar has a small surface area at its apex, allowing for nanoscale magnet-NV center distances [37]. Fabrication details can be found in Refs. [36,44].

The presence of a magnetic field perpendicular to the NV center quantization axis limits NV spin readout contrast, photoluminescence intensity, and coherence time $T_{2,e}$ in a natural abundance ^{13}C diamond [45]. To align the magnetic field and characterize the field distribution, we scan the micromagnet with respect to the diamond nanopillar with a three-axis stack of piezoelectric nanopositioners. At each position, we optically measure the electron spin resonance (ESR) and calculate the magnetic field along the NV center quantization axis (see Supplemental Material [46]); an example map of the magnetic field around a micromagnet is shown in Fig. 2(a). With our current smallest micromagnet-NV distance of ∼1.0 μm, we estimate gradients exceeding 1.5×10^4 T/m, corresponding to an expected single-phonon spin-mechanical coupling strength of $\lambda/2\pi \sim 5$ Hz [Fig. 2(b)].

Preservation of spin coherence in proximity of a transported micromagnet.—Next, to investigate whether the spin coherence can be maintained during qubit transport, we perform a proof-of-principle experiment in which we move the micromagnet 1.7(2) μm away from the diamond nanopillar and then back to its original position. Pulsed ESR measurements at different times during the movement sequence [Fig. 3(a)] reveal a significant change in the magnetic field environment, as evidenced by a shift of 9.8(1) MHz in the ESR frequency [46].

We demonstrate the preservation of spin coherence in proximity of a transported micromagnet, using the pulse sequence in Fig. 3(b) synchronized with the movement sequence in Fig. 3(a). Since the total movement time of 1.7 ms is significantly longer than the electronic spin coherence time of 0.95(4) ms [46], we use the NV center's intrinsic ^{15}N nuclear spin as a quantum memory [47,48].

Specifically, in our demonstration, the electron and ^{15}N nuclear spin are first initialized in a two-qubit register $|-1\rangle_e \otimes |\downarrow\rangle_n$ [46], followed by a $\pi/2$ pulse which puts the ^{15}N nuclear spin in a superposition $|-1\rangle_e \otimes (|\downarrow\rangle + |\uparrow\rangle)_n$. Subsequently, we apply a $\mathrm{C_nNOT_e}$ gate that fully entangles the electron-nucleus pair $-|0\rangle_e|\downarrow\rangle_n + |-1\rangle_e|\uparrow\rangle_n$.

During the subsequent free evolution time τ, the entangled electron-nucleus pair accumulates a phase $\phi(\tau)$.

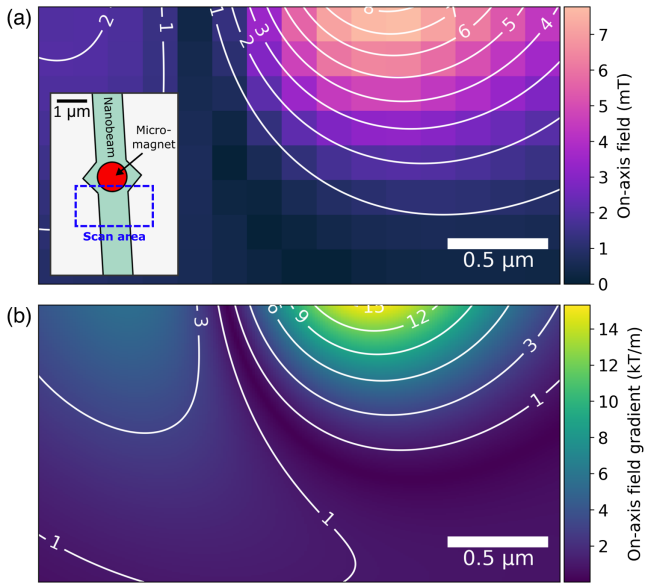

FIG. 2. Magnetic field imaging of a micromagnet. (a) Magnetic field near the micromagnet, with a vertical NV-magnet separation of about 1 μm. For each position of the diamond nanopillar, we measure the ESR frequencies, from which we extract the magnetic field along the NV center's axis [46]. The field from the spherical micromagnet is well approximated by a dipole model, with the fit (contours) deviating from the measured fields by less than 3 G at any point. The orientations of the NV center and magnet are consistent with the fabrication process of the nanopillar and magnetization direction, respectively. These measurements were performed in air at room temperature, without any external driving of the mechanical resonator. Inset: diagram showing the scanning area around the micromagnet on the nanobeam. (b) Reconstructed magnetic field gradients based on fit to dipole model. The maximum gradient is $\sim 1.5 \times 10^4$ T/m.

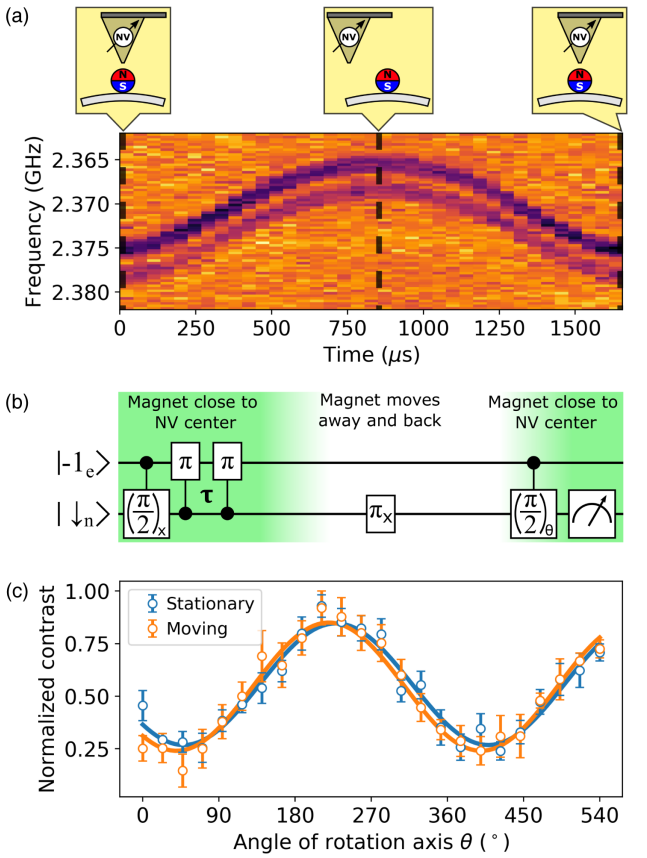

FIG. 3. Preservation of spin coherence in proximity of a transported micromagnet. (a) The nanobeam along with the micromagnet is moved 1.7(2) μm from the NV center and then back to its original position over 1.7 ms. Pulsed ESR measurements at different times during the movement sequence show the changing field from the moving micromagnet. The 3 MHz hyperfine splitting from the NV center's intrinsic ^{15}N nuclear spin is clearly visible; an additional hyperfine splitting from a nearby ^{13}C nuclear spin is not shown here due to the microwave pulse duration used [46]. (b) Pulse sequence used to demonstrate storage and retrieval of coherent information, synchronized with the movement sequence shown in (a). (c) Fixing the phase accumulation time $\tau = 900$ ns, we measure the coherence of the nuclear spin at the end of the movement sequence by varying the rotation axis angle θ of the final $\pi/2$ pulse, for both cases where the micromagnet is moved (orange) and kept stationary (blue).

For the particular NV center in our measurements, hyperfine interactions with a nearby ^{13}C nuclear spin lead to phase accumulation at a rate of $\sim$0.9 MHz. A second C_nNOT_e gate then disentangles the electron-nuclear pair and the phase information $\phi(\tau)$ is now entirely stored in the ^{15}N nuclear spin $|-1\rangle_e \otimes (-|\downarrow\rangle + e^{i\phi(\tau)}|\uparrow\rangle)_n$.

As shown in Fig. 3(a), the field at the nanopillar changes significantly during the movement sequence, leading to an additional phase accumulation on the ^{15}N. We eliminate this additional phase by applying a π pulse on the ^{15}N near the middle of the movement sequence [46]. Finally, a $\pi/2$ pulse at the end of the movement sequence converts the stored phase information $\phi(\tau)$ into the probability of finding the ^{15}N in either $|\downarrow\rangle_n$ or $|\uparrow\rangle_n$, which can be measured with a boost in signal-to-noise ratio using repetitive readout [49].

By fixing $\tau = 900$ ns $< T^*_{2,e}$ and varying the rotation axis angle of the final $\pi/2$ pulse, we can quantify the spin coherence preservation. The results, shown in Fig. 3(c) demonstrate that the normalized contrasts for cases where the micromagnet is moved (orange) and kept stationary (blue) are 0.61(3) and 0.57(3), respectively, indicating that the nuclear spin coherence is unaffected by the significant change in magnetic field.

Mechanical motion and single-phonon coupling strength.—Finally, we characterize the spin-mechanical coupling by exciting the nanobeam and characterizing its mechanical motion via independent measurements with both an interferometer and the nearby NV center. To take advantage of higher quality factors at low temperatures, we use the scanning probe setup in a helium cryostat. The interferometric measurements, shown in Figs. 4(a) and 4(b), reveal a quality factor of $8.25(6) \times 10^5$

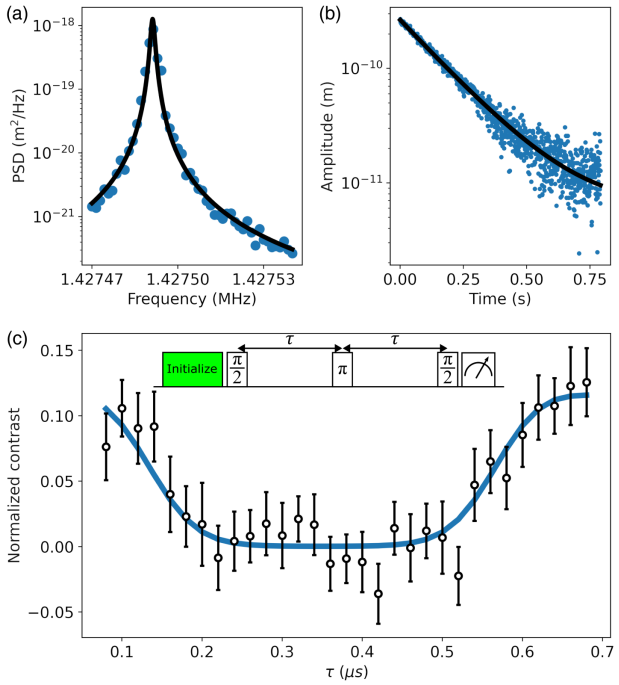

FIG. 4. Sensing the mechanical motion of the nanobeam. (a) Power spectral density (PSD) of the mechanical mode, measured using an interferometer. From the Lorentzian fit (black line) we extract a resonance frequency of ∼1.4 MHz and a linewidth of $\kappa/2\pi = 1.5(2)$ Hz. (b) After switching off an external drive from a piezoelectric chip, we measure the amplitude decay of the mechanical motion and obtain $Q = 8.25(6) \times 10^5$. (c) Sensing of the mechanical motion with the NV center. We perform a Hahn echo pulse sequence on the NV center with and without the mechanical drive and plot their ratio (black circles) such that we can neglect the NV center's decoherence in our model for the fit [$\chi(\tau)$, blue line]. We fit the signal $S(\tau, \lambda, \Delta_x)/e^{-\chi(\tau)}$ [see Eq. (1)] to find $\lambda/2\pi = 7.7(9)$ Hz. Because of drift in the cryogenic setup, the sweep of τ is limited to 700 ns to capture the first collapse in coherence due to the effect of the mechanical motion.

[Fig. 4(b)], demonstrating that the quality factor remains high despite magnetic functionalization [46]. The mechanical frequency $\omega_r/2\pi \sim 1.4$ MHz [Fig. 4(a)] corresponds to a period of 0.7 μs. As a result, the mechanical resonator can undergo multiple oscillations during the spin coherence time $T_{2,e}$, which is around several microseconds. The readily accessible high mechanical frequency of the nanobeam compares favorably to other spin-mechanical platforms, such as those featuring cantilevers, nanowires, and magnetic levitation [13,17,23].

Near the micromagnet, the NV center experiences a Zeeman shift, which can be expanded in the resonator displacement to give the interaction Hamiltonian $\mathcal{H}_{\text{int}} = \gamma_e z_p \nabla_z (\hat{a} + \hat{a}^\dagger)$, where γ_e is the NV center electronic spin gyromagnetic ratio, ∇_z is the magnetic field gradient along the NV center quantization axis, z_p is the mechanical zero-point motion, and a is the mechanical mode annihilation operator. To quantify the single-phonon spin-mechanical coupling strength $\lambda = \gamma_e z_p \nabla_z$, we excite the nanobeam with an external broadband drive and detect the field from the oscillating micromagnet with the nearby NV center. We use a Hahn echo pulse sequence, which results in frequency-dependent detection of the magnetic spin environment (see Supplemental Material [46]). Sweeping the time τ between the π pulses and assuming a Gaussian distribution of the mechanical state, the spin contrast can be approximated as

$$S(\tau, \lambda, \Delta_x) = \alpha e^{-8\Delta_x^2 \lambda^2 \sin^4(\omega_r \tau/2)/\omega_r^2 z_p^2} e^{-\chi(\tau)}, \tag{1}$$

where Δ_x is the rms amplitude of motion, α is the spin readout contrast, and $\chi(\tau)$ describes the coherence decay from other noise sources in the diamond, such as the bath of ^{13}C nuclear spins [45,46].

To determine λ, we first independently quantify Δ_x by integrating the interferometer signal of the mechanical response from the wideband drive and assign ω_r to the center frequency. For the data corresponding to Fig. 4(a), we find that $\Delta_x = 1.86(1)$ nm, far above the rms thermal motion of 9 pm. We then fit the Hahn echo data, normalized to a baseline Hahn echo measurement (without driving the mechanical resonator) to compensate for intrinsic NV decoherence $e^{-\chi(\tau)}$ [Fig. 4(c), black dots]. For the fit (blue line), λ is the only free parameter, while ω_r and Δ_x are fixed, and $z_p = \sqrt{\hbar/2m_{\text{eff}}\omega_r} = 11$ fm for an effective mass $m_{\text{eff}} = 4.6 \times 10^{-14}$ kg. We find that $\lambda/2\pi = 7.7(9)$ Hz [Fig. 4(c)], corresponding to a gradient of $2.4(1) \times 10^4$ T/m, similar to the gradients from the static field imaging of the same magnet [Fig. 2(b)].

Discussion and outlook.—Our experiments demonstrate the feasibility of the proposed architecture for programmable mechanically mediated interactions between distant spins. Specifically, we showed that the NV center's intrinsic nuclear spin memory is not degraded by transport of a nearby micromagnet, if the proper decoupling pulse sequences are applied. The demonstrated movement distance of 1.7(2) μm in Figs. 3(a)–3(c) significantly exceeds the range of magnetic dipole-dipole interactions between spins and is limited by the moving speed of 1 mm/s and nuclear spin coherence time $T_{2,n} \sim 5$ ms [46]. The speed can be increased by using a nanopositioner with a higher bandwidth and minimizing residual vibrations caused by the scanning motion. By decoupling the nuclear spin from its local environment or cooling to cryogenic temperatures, $T_{2,n}$ can be extended to > 1 s [2,50], which would extend the possible distance to > 1 mm even with the current speed.

At the same time, achieving quantum coherent spin-mechanical coupling [14,26,27,29,51,52] requires increasing the coupling strength while minimizing noise. Specifically, the onset of coherent quantum phenomena is generally marked by the spin-mechanical cooperativity

$C \equiv (\lambda^2/\Gamma\kappa n_{th}) \gtrsim 1$, which compares the coherent-coupling rate λ to the dissipation rates Γ, κn_{th} of the spin and mechanical mode, respectively. While the cooperativity of our present experiment exceeds previous spin-mechanical platforms involving NV centers [46], its value of 10^{-7} remains far below the coherent-coupling regime. However, significant improvements can be made. Drift of the NV-magnet distance causes significant variations of the ESR frequency at high magnetic field gradients, limiting our current gradient to 2.4×10^4 T/m at a distance of 1.0 μm. With improvements to the setup stability and the use of atomic-force microscopy feedback [36,53], positioning the NV center at a reduced distance of 50 nm from the surface of a 1 μm-diameter micromagnet should yield gradients $\sim 1.4 \times 10^6$ T/m or a spin-mechanical coupling of $\lambda/2\pi \sim 800$ Hz. The doubly clamped nanobeam can be replaced with recent designs that utilize strain engineering and soft clamping, which have demonstrated $Q \sim 10^9$ at megahertz frequencies [31,32,34,35,54]. Even higher quality factors have been demonstrated or predicted, by replacing silicon nitride with crystalline materials such as silicon and diamond [55,56]. For a coupling strength of $\lambda/2\pi = 800$ Hz, an NV center electronic spin coherence time $T_{2,e}$ of 10 ms [7,57], and a quality factor of 10^9 at 4 K, the coherent-coupling regime is possible with $C \sim 75$. Under such conditions, mechanics-mediated entanglement of electronic spins with fidelity exceeding 95% should be feasible according to the proposal in [27]. Although we expect $T_{2,e}$ to improve with larger NV implantation depth, further investigation into diamond fabrication and surface termination might be required to increase $T_{2,e}$ to the 10 ms regime for NV centers in diamond nanopillars [58,59].

Compared to previous work involving on-chip, circuit-based hybrid quantum systems [11,30], a spin-mechanical architecture featuring dynamical qubit transport has the advantage of being able to generate programmable, nonlocal interactions, similar to reconfigurable platforms based on neutral atoms and trapped ions. The long coherence time of the nuclear spin allows multiple distant spins to be dynamically transported to interact with the same mechanical bus. While Fig. 1 only shows one mechanical resonator for clarity, the architecture can also be parallelized, with multiple mechanical resonators simultaneously mediating interactions within large arrays of spins. We also note that, unlike most other hybrid quantum systems [23,30], both the mechanical and spin components of our platform are highly coherent even at room temperature. With a nanomagnet diameter of 0.3 μm, an NV-magnet separation of 20 nm, spin coherence time of $T_{2,e} = 2$ ms [60], and $Q = 1 \times 10^9$, reaching the coherent-coupling regime at room temperature appears feasible. We note that, while our Letter focuses on NV centers, the core concept applies to other solid-state spin qubits such as silicon-vacancy centers in diamond and color centers in silicon carbide, which have been incorporated into nanopillarlike structures [61–64]. The above considerations indicate that, with realistic improvements, our platform can enable programmable interactions between distant spins, opening up a new avenue toward scalable quantum information processing with solid-state spin qubits. The ability to generate scalable long-range interactions between quantum sensors also presents new opportunities in entanglement-enhanced sensing with applications in condensed matter studies. Finally, the present approach can be extended to realize other hybrid systems by coupling spin qubits to quantum systems, such as superconducting qubits and optical photons [25,65–67].

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