Efficient Entanglement of Spin Qubits Mediated by a Hot Mechanical Oscillator

Emma Rosenfeld,¹,† Ralf Riedinger,¹ Jan Gieseler,¹,‡ Martin Schuetz,²,³,‡ and Mikhail D. Lukin¹

¹Physics Department, Harvard University, Cambridge, Massachusetts 02318, USA
²Amazon Quantum Solutions Lab, Seattle, Washington, D.C. 98170, USA
³AWS Center for Quantum Computing, Pasadena, California 91125, USA

(Received 5 November 2020; accepted 29 April 2021; published 24 June 2021)

Local electronic and nuclear spin qubits in the solid state constitute a promising platform for storage and manipulation of quantum information, even at room temperature. However, the development of scalable systems requires the ability to entangle distant spins, which remains a challenge today. We propose and analyze an efficient, heralded scheme that employs a parity measurement in a decoherence free subspace to enable fast and robust entanglement generation between distant spin qubits mediated by a hot mechanical oscillator. We find that high-fidelity entanglement at cryogenic and even ambient temperatures is feasible with realistic parameters and show that the entangled pair can be subsequently leveraged for deterministic controlled-NOT operations between nuclear spins. Our results open the door for novel quantum processing architectures for a wide variety of solid-state spin qubits.

In this Letter, we propose and analyze a fast and robust entanglement protocol for two spins (with eigenstates $|0\rangle$ and $|1\rangle$), linearly coupled to a common mode of a high-temperature mechanical resonator [Fig 1(a)] via parity

In a complementary approach, Rabl et al. [8] suggested transducing interactions via magnetically functionalized oscillators, leveraging recent advances in the control of micromechanical resonators [9,10], which enables quantum control of solid-state electron spins [11–15]. Robustness against thermal noise is desirable for such applications at elevated temperatures to avoid phonon-induced gate errors [16]. Previous approaches for such “hot” gates require large qubit-resonator cooperativities $C \gg 1$ for low error rates [17] with error scaling as $\mathcal{E} \propto 1 / \sqrt{C}$ ($C \equiv \lambda^2 / \Gamma \eta_{\text{th}}$ compares the coherent coupling rate $\lambda$ to the dissipation rates of the spin and resonator, $\Gamma$ and $\kappa \eta_{\text{th}}$, respectively). These regimes are experimentally challenging to achieve, such that a demonstration of mechanically mediated entanglement remains elusive.

FIG. 1. Entanglement protocol. (a) Two qubits are coupled with equal strength $\lambda$ to a high $Q$ resonator that is independently measured and has the thermal occupation $n_{\text{th}} \gg 1$. (b) Spin-dependent resonator potential. Spin states $|0\rangle$, $|1\rangle$ are decoupled, whereas $|00\rangle$, $|11\rangle$ shift the potential, such that toggling between them every half period drives the resonator. (c) The spins are initialized in $|+\rangle$, and the resonator states before ($M_1$) and after ($M_2$) applying the spin pulse sequence (black) for duration $t_j$, are compared. Absence of displacement indicates spins are in the entangled antiparallel states. (d) Proposed implementation. A diamond with NV centers is placed near a microresonator (gray) functionalized with nanomagnets (black), which is measured interferometrically. The entangled NV spin state is used to teleport gates between proximal $^{13}$C or $^{15}$N nuclear spins.
measurements in a decoherence-free subspace (DFS) [18–21]. The Bell states $|Ψ^+\rangle \propto |01\rangle \pm |10\rangle$ decouple from the resonator, forming a DFS insensitive to its thermal fluctuations. In contrast, the aligned states $|00\rangle$ and $|11\rangle$ exert a force on the oscillator, resulting in a large, observable displacement [Fig 1(b)]. We can thus herald the entangled $|Ψ^+\rangle$ state by monitoring the absence of an excess force on the mechanical oscillator, constituting a (half) parity measurement in a measurement-free subspace [19,20,22] analogous to previous proposals considering atoms in optical cavities [18]. By design, this protocol is robust to thermal noise and does not require strong coupling or cooling to the mechanical ground state. We show that entanglement can be generated at high success rates with relaxed cooperativity requirements, $C \gtrsim 1$, and with error scaling approaching $\tilde{E} \propto \ln(C)/C$ at large cooperativities. We specifically analyze an experimental realization involving NV centers in diamond coupled to magnetically functionalized mechanical nanobeam resonators [12,13,15,23], but note that our protocol can equally be applied to other qubit species coupled to bosonic modes at high temperatures [24–34], even when high-fidelity readout is not available by other means [11,35–37].

The entangled pair of electronic spins can be subsequently leveraged to herald two-qubit gates between nearby, coherently coupled nuclear spin memories in the solid state [Fig 1(d)]. Assuming state-of-the-art quality ($Q$) factors, spin-mechanics coupling strength, and spin coherence times [9,38–41], we expect that our entangling gate can achieve error rates below 1% at cryogenic temperatures. With modest improvements in the coupling strength, similarly low error rates can be achieved at room temperature.

Entanglement protocol.—The key idea of our approach can be understood by considering two spin qubits, characterized by the Pauli operators $σ_x^{(i)}$ ($i = 1, 2$), that are linearly coupled with equal strength $\lambda$ to a micromechanical oscillator [Fig. 1(a); see the Supplemental Material (SM) [42], which contains Refs. [43–53], for inhomogeneous $\lambda$]. If the qubit frequencies $ω_x^{(i)}$ ($i = 1, 2$) strongly exceed that of the resonator $ω_r$, the transverse coupling terms can be ignored, and the system Hamiltonian is

$$\hat{H}/\hbar = \frac{ω_r^{(1)}}{2} σ_x^{(1)} + \frac{ω_r^{(2)}}{2} σ_x^{(2)} + ω_r a^+ a + \lambda S_z (a + a^+) ,$$  

where $S_z = σ_z^{(1)} + σ_z^{(2)}$ and $a (a^+)$ are the bosonic annihilation (creation) operators of the resonator mode. For the two states $|01\rangle$ and $|10\rangle$, the qubits are decoupled from the resonator: the $S_z = 0$ states comprise a DFS, i.e., their phase is independent of the mechanical state. The other two states exert a force $\sim ± 2\hbar ω/\zeta_p$ on the resonator, where $\zeta_p$ is the mechanical zero point fluctuation.

In our entanglement protocol [Fig. 1(c)], (i), the state of the resonator is first measured, while the two spins are initialized in the separable state $|+\rangle \otimes |+\rangle \propto \sqrt{2} |Ψ^+\rangle + |11\rangle + |00\rangle$, with $|+\rangle = (|1\rangle + |0\rangle)/\sqrt{2}$. Then, (ii) the spins interact with the resonator for a time $t_f$ while being subject to a special resonant decoupling sequence such that the spin states $|11\rangle$ and $|00\rangle$ displace the resonator state. Finally, (iii) the resonator displacement is measured. If it is below a threshold, the spins are projected into the Bell state $|Ψ^+\rangle$, indicating successful entanglement generation. The protocol can be made deterministic by repeating steps (i)–(iii) until success ($\sim 2–3$ repetitions in the regime of interest).

To estimate its practical performance, we assume the mechanical system can be described by a master equation and is weakly coupled ($Q \gg 1$) to a hot thermal bath at rate $κ = ω_r/Q$ and temperature $T = hω_r/k_B$. We also assume each qubit is dispersively coupled to an independent reservoir with dephasing rate $Γ$. The Gaussian state of the oscillator can be estimated interferometrically and independently of the spins. In practice, the effects of the measurement backaction and duration are negligible in near term realizations (see the SM). To simplify the derivation, in the following we assume short backaction evading measurements of the mechanical quadrature [54], neglecting the measurement duration and avoiding a lower limit on the measurement uncertainty.

Figure 2 illustrates the key ingredients of the scheme. In step (i), we perform an initial linear measurement $M_1$ on the momentum quadrature $p ≡ i(a^+ − a)/\sqrt{2}$, with measurement uncertainty $Δm$ [Fig. 2(a)]. In step (ii), the spins are resonantly coupled to the oscillator by a series of $π$ pulses (here assumed to be ideal), with a pulse separation $2τ = π/ω_r$. This simultaneously maximizes the conditional mechanical displacement and the spin coherence by dynamically decoupling from their bath [Figs. 1(b) and 1(c)]. Throughout this pulse sequence, the force acting on the resonator is a square wave with amplitude $\sim −h\lambda S_z /\zeta_p$ [Fig. 1(c)] and frequency $ω_r$. In the high $Q$ limit, higher harmonics of the force can be neglected, resulting in the effective interaction Hamiltonian in the rotating and toggling frame under a rotating wave approximation [42]:

$$\hat{H}_{\text{int}}/\hbar = \frac{2τ}{π} S_z (a^+ + a),$$  

leading to a momentum shift of the resonator $μ(S_z, t_f) = −4\sqrt{2} Δt S_z (1 − e^{−κτ_f}/πk ≈ −2\sqrt{2Δt} S_z /Δm^2$ in natural units for $κτ_f ≪ 1$. As the conditional equations of motion are linear, the motional states after step (ii) remain Gaussian with an uncertainty $Δd(t_f) ≈ \sqrt{κτ_F S_z} + Δm^2$ [dashed circles in Fig. 2(b)] and a spin-dependent expectation value of the momentum quadrature of $M_2 e^{−κτ_f}/π + μ(S_z, t_f)$. Then, (iii) a second measurement $M_2$ localizes the resonator with uncertainty $Δm$, projecting the spin population
Δα positive acceptance (h an the displacement Δ momentum difference measured again (Gaussian) probability density function onto the momentum basis used to define a threshold to Sz; Sz lies within this threshold, Sz = 0 if the distributions are separable. If this is achieved within the coherence time 1/Γ of the spins, an ⟨Sz⟩ = 0 measurement projects the two spins into the entangled state |Ψ+⟩.

A simple estimate shows the minimum requirements for this protocol. For negligible measurement uncertainties Δm ≡ kωth/t and an interaction time comparable to the spin coherence time tI ≈ 1/Γ yet shorter than the mechanical lifetime tI ≈ 1/κ, the distributions become separable if the displacement |μ(2, 1/Γ)|/2 exceeds the uncertainty Δ|tI|/2, i.e., Δm²/4kωth = C ≥ 1.

To obtain an estimate of the fidelity, we compute the (Gaussian) probability density function P(Sz, ΔM) of the momentum difference ΔM ≡ M2 − e−kωth/2M1, conditional on the spin state Sz, which has expectation value μ(Sz, tI) and variance

σ(tI)² = Δm²(1 + e−kωth) + nωth(1 − e−kωth) (3)

corresponding to the contributions by the measurement uncertainties and diffusion during the interaction. The state is assumed to have Sz = 0 if

|ΔM| < αμ(2, tI)/2, (4)

where the threshold α ∈ (0, 1] can be tuned to trade between a high acceptance rate (α → 1) and low false positive acceptance (α → 0). The probability of an accepted event being a true positive is

S(α, g(tI)) = 1/[1 + e−2g(tI)²] − O(α²),

given by the integrals of P_{0,1} within the thresholds and weighted by the initial spin populations [42], where we define the normalized displacement g(tI) ≡ μ(2, tI)/2σ(tI). The error in entanglement fidelity F = ⟨Ψ±|ρ|Ψ±⟩ is the result of two independent error sources, namely spin dephasing and false positive ⟨Sz⟩ = 0 assignments, yielding

F = 1 + e−2g(tI)

It follows directly that entanglement can be generated (F > 1/2) for g(tI)² > ΓtI. We note that this simple estimate for α → 0 is a good approximation for general F [42].

Analysis of the Bell state preparation.—In the following, we consider the experimentally relevant regime Δm² ≪ kωth/tI, i.e., the linearized diffusion term dominates the variance of ΔM and that κtI ≪ 1. In these limits, such that F can be described only in terms of α, C, and ΓtI [Fig. 3(a)]. The fidelity exceeds 1/2 for C > π²/8 ∼ 1.2

![FIG. 2. Mechanical phase space picture.](image)

![FIG. 3. Performance.](image)
and exceeds 96% for $C \sim 100$, demonstrating that our protocol can be applied with relatively low $C$. The optimal interaction time $\Gamma t^*$ is determined numerically for each $C$ [Fig. 3(b), dashed lines] and can be analytically approximated as

$$\Gamma t^* \approx \frac{\pi^2}{16C} \ln\left(\frac{16C}{\pi^2 - 1}\right)$$

(7)

for $C > \pi^2/8$ and $\Delta m, \alpha \to 0$ [42], showing that the entanglement protocol is fast compared to the spin coherence time. We note that, in the regime of interest ($C \gtrsim 8$, $t_I \ll 1/\Gamma$), decreasing the threshold $\alpha$, e.g., from 1 to 0.5, reduces the optimal interaction time [Fig. 3(b)]. At high $C$, this can compensate the reduced acceptance rate for small $\alpha$ and increase the absolute rate of true positive entanglement heralding events given by $r_p = \int_{-\theta}^{+\theta} \mathcal{P}_0(p) dp / 2\theta^*$ for threshold $\theta = a\mu(2, t^*)/2$ [Fig. 3(d)] [42]. Inserting Eq. (7) into Eq. (5), we find a lower bound to the fidelity

$$\mathcal{F} \geq \frac{1}{2} \left( \frac{1 + (16C/\pi^2 - 1)^{-\pi^2/8C}}{1 + (16C/\pi^2 - 1)^{-1}} \right)$$

(8)

again for $C > \pi^2/8$ and $\Delta m, \alpha \to 0$. The error $\mathcal{E} = 1 - \mathcal{F}$ is shown in Fig. 3(c). Remarkably, the cooperativity required to achieve an error $\mathcal{E} < 10^{-3}$ is more than 2 orders of magnitude lower than for previous mechanically mediated gates [8,17]. For large $C$, $\mathcal{E} \sim (\pi^2/16) \ln(C)/C$.

Potential applications.—The entanglement protocol presented here is inherently probabilistic, approaching a heralding probability of 1/2 for $\alpha \to 1$. However, it can be extended to yield deterministic controlled-NOT gates, as required for quantum information processing, between associated qubit registers by feedback, assuming a simple repeat-until-success scheme [4,18]. In the following, we consider two electronic spins, such as NV centers (using $|m_s\rangle = |\pm 1\rangle$) as qubit states for maximal displacements), interacting with the mechanical resonator and coupled to nearby $^{13}\text{C}$ (or $^{15}\text{N}$) nuclear spins in the diamond host [Fig. 1(d)]. The entangled NV spin state is used to teleport a gate between the nuclear spins [59]. Contributions to the gate error $\mathcal{E}_T$ include infidelities related to the ideal entanglement protocol $\mathcal{E}_c$, control ($\mathcal{E}_C$), initialization ($\mathcal{E}_{\text{init}}$), and readout ($\mathcal{E}_{\text{RO}}$) of the NV spins, and the electron-nuclear CNOT gate ($\mathcal{E}_{\text{CNOT}}$). Nuclear qubit errors arise from coupling to a bath ($\mathcal{E}_{\text{nuc}}$) at rate $\gamma_N/\gamma_e$, where $\gamma_N$ ($\gamma_e$) is the nuclear (electron) gyromagnetic ratio, as well as dephasing due to electron spin control errors in failed entanglement attempts. As the latter depends on the heralding probability and the hyperfine coupling, we attribute it to $\mathcal{E}_C$ with a factor $\eta$, which is below 1 in the regime of interest [42]. Combining state-of-the-art spin control [60,61] with robust decoupling sequences [62], $\mathcal{E}_C$ can be neglected. However, if left unaddressed without optimal spin control, $\mathcal{E}_C$ can limit the fidelity [7]. As the repetition rate is high [Figs. 3(b) and 3(d)], we further neglect the small probability of failure after a large number of repetitions in a synchronous circuit [4]. In this case, the total error of the deterministic nuclear gate is $\mathcal{E}_T = \mathcal{E} + \delta(1 + \eta)\mathcal{E}_C + \mathcal{E}_{\text{init}} + \mathcal{E}_{\text{RO}} + \mathcal{E}_{\text{CNOT}} + \mathcal{E}_{\text{nuc}}$.

Experimental implementation.—In NV-based operations on nearby nuclear spins, optical excitation of the NV induces decoherence on the nuclear spins through the hyperfine coupling [6,7,63,64], which can limit $\mathcal{E}_T$ due to repeated spin initialization and readout unless compensated by a DFS of nuclear spins [65]. In our system, the mechanical oscillator can also be used for single-shot readout and initialization [11], eliminating the need for optical illumination of the color center [66].

While state-of-the-art continuous interferometric measurement schemes are sufficient for initial experiments [38,40], their performance could be optimized using a multiple model adaptive estimation [68,69] to account for mechanical spectator modes and other technical noise sources [42]. For further improvement, the estimation of the spin-induced displacement can be achieved with a multiple model adaptive estimation [68,69], while performing steps (ii) and (iii) simultaneously, as well as feedback on the spin state with additional global spin rotations during the pulse sequence, further increasing the entanglement fidelity and rate [21]. Finally, errors arising from small inhomogeneities in the coupling strength can be suppressed with additional electron spin control [42].

Figure 4 shows the controlled-NOT gate error $\mathcal{E}_T$ as a function of $C$. For realistic parameters described in [42], at very high $C$, the total error $\mathcal{E}_T$ is limited by the electron-nuclear two qubit gate fidelity, while at more modest cooperativity, the error scales favorably compared to the existing state of the art [17]. Note that an experimental demonstration of our protocol (with $\mathcal{E}_T \sim 10^{-1}$) may be
possible at room temperature and $C \sim 8$, corresponding to state-of-the-art spin-mechanical systems ($1/\Gamma \sim 10$ ms [70]; $Q \sim 10^9$ [9,71]; $\lambda/2\pi \sim 0.9$ kHz [41]; $\Delta m^2 \sim 27$ [40]). These parameters are within reach for a soft-clamped, silicon nitride nanobeam resonator, functionalized with a nanomagnet at the antinode of motion and placed adjacent to diamond hosting NV centers [Fig. 1(d)] [70,71]. A modest further improvement in the spin-mechanical coupling strength ($\lambda \sim 2$ kHz) enables high-fidelity gates ($\mathcal{E}_T < 10^{-3}$). Conversely, at cryogenic temperatures ($T \sim 4$ K, coherence time $1/\Gamma \sim 1$ s [70,72]) the same system can achieve this fidelity already with $\lambda/2\pi \sim 100$ Hz [42]. Such parameters yield a high probability of success (approaching 50% per run) and an average gate duration approaching 10 ms, faster or comparable to deterministic protocols with the reported coupling strengths [17].

**Conclusion.**—We proposed and analyzed a half-parity measurement protocol in a decoherence free subspace for entangling two qubits through a hot resonator, with error scaling that nears $\mathcal{E} \propto \ln(C)/C$. Our protocol is fast and robust to thermalization errors, and it does not require ground state cooling. A teleported controlled-NOT gate employing the generated Bell pair is feasible with magnetically functionalized resonators and solid-state electronic spins featuring long coherence times [70,71]. While we analyzed an implementation involving NV centers, the protocol can also be applied to other promising paramagnetic defects, such as spins in silicon [75], as readout and initialization can be realized mechanically [11]. Further directions for analysis include leveraging continuous feedback to increase the entanglement rate [21,22,76] and the application of our protocol to generate multipartite entangled states. Finally, for further improvements, nanobeam resonators can be electrostatically coupled [8] using hybridized mechanical modes to selectively couple spins adjacent to distinct resonators, enabling multiqubit connectivity far beyond the reach of the magnetic dipole-dipole interactions. While our work leverages decades of development of micromechanical devices and solid-state qubits, it simultaneously eliminates the need for high-fidelity single qubit optical or electronic addressing. With substantial technical improvement beyond the current state of the art, in the long term this approach could pave the way for realization of solid-state, room-temperature quantum information systems.

We would like to thank S. Hofer for insightful discussions and Samantha Dakoulas for assistance during this project. The authors thank C. Maxwell for design assistance with Figs. 1 and 2. This work was supported by NSF, CUA, ARO MURI, and V. Bush Faculty Fellowship. R. R. was supported by the Alexander von Humboldt Foundation. This material is based upon work supported by the National Science Foundation Graduate Research Fellowship under Grants No. DGE1144152 and No. DGE1745303. This work was supported by DOE, Grant No. DE-SC0020115. Any opinion, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.


[71] A. H. Ghadimi, S. A. Fedorov, N. J. Engelsen, M. J. Degen, M. Markham, D. J. Twitchen, and A. H. Bakker, M. J. Degen, M. Markham, D. J. Twitchen, and


