A silicon quantum-dot-coupled nuclear spin qubit

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Single nuclear spins in the solid state are a potential future platform for quantum computing\(^{13,14}\), because they possess long coherence times\(^{12,13}\) and offer excellent controllability\(^{13}\). Measurements can be performed via localized electrons, such as those in single atom dopants\(^{15,16}\) or crystal defects\(^{10,11}\). However, establishing long-range interactions between multiple dopants or defects is challenging\(^{18,19}\). Conversely, in lithographically defined quantum dots, tunable interdot electron tunnelling allows direct coupling of electron spin-based qubits in neighbouring dots\(^{20,21}\). Moreover, the compatibility with semiconductor fabrication techniques\(^{21}\) may allow for scaling to large numbers of qubits in the future. Unfortunately, hyperfine interactions are typically too weak to address single nuclei. Here we show that for electrons in silicon metal–oxide–semiconductor quantum dots the hyperfine interaction is sufficient to initialize, read out and control single \(^{29}\)Si nuclear spins. This approach combines the long coherence times of nuclear spins with the flexibility and scalability of quantum dot systems. We demonstrate high-fidelity projective readout and control of the nuclear spin qubit, as well as entanglement between the nuclear and electron spins. Crucially, we find that both the nuclear spin and electron spin retain their coherence while moving the electron between quantum dots. Hence we envision long-range nuclear–nuclear entanglement via electron shuttling\(^{13}\). Our results establish nuclear spins in quantum dots as a powerful new resource for quantum processing.

Electrons bound to single dopant atoms or localized crystal defects strongly interact with the host donor or defect nuclear spins\(^{21}\), as well as nearby lattice nuclear spins\(^{22,23}\), due to their highly confined wavefunctions. In quantum dots, the electron wavefunction is less confined and typically overlaps with many more nuclear spins, leading to undesired effects such as loss of coherence and spin relaxation\(^{22,23}\). In silicon metal–oxide–semiconductor quantum dots, however, the strong confinement of the electrons against the Si–SiO\(_2\) interface, together with the possibility of small gate dimensions, results in a relatively small electron wavefunction\(^{24}\) (Fig. 1a,b). The confined wavefunction yields strong hyperfine interactions. Using isotopically enriched \(^{28}\)Si base material, only a few \(^{29}\)Si nuclei may interact with the electron. Simulations of the distribution of expected hyperfine couplings\(^{25}\) in a quantum dot with an 8 nm wavefunction diameter and 800 ppm \(^{29}\)Si nuclei indicate an expectation of two to three \(^{29}\)Si nuclei per quantum dot that have a resolvable hyperfine coupling (>100 kHz), and a maximally possible hyperfine coupling of ~400 kHz (Extended Data Fig. 1).

**Fig. 1** Hyperfine coupling in a silicon metal–oxide quantum dot. **a.** Schematic of the device layout, which consists of a double quantum dot formed under accumulation gates G1, G2 and laterally confined by gate C. Gate GT controls the tunnel coupling to a nearby electron reservoir. **b.** Close-up of the interface region, showing an electron wavefunction (7 nm diameter) with vertical valley oscillations (blue lobes), projected over the silicon lattice (grey dots). The overlap of the wavefunction with nearby \(^{28}\)Si spins (green), shown here with random locations at 800 ppm density, determines the respective hyperfine coupling rates\(^{25}\). Simulations yield the probability to find a nuclear spin with a particular hyperfine coupling rate (Extended Data Fig. 1). Shown is one instance where the larger green spin indicates a 450 kHz coupled location. **c.** Scanning electron micrograph (SEM) of the device layout, also showing the reservoir accumulation gate (RES), a nearby single electron transistor (SET) to determine electron occupation and an on-chip antenna (MW) to drive electron or nuclear spin resonance. **d.** Left: when monitoring the ESR centre frequency, extracted by fitting repeated ESR frequency scans, bimodal jumps can be observed on a timescale on the order of hours. Right: a histogram of the centre frequencies reveals the presence of a coupled nucleus (green spin), with hyperfine coupling \(|A| \approx 450 kHz and a second \(|A_1| \approx 120 kHz\) coupled nucleus (red spin). The histogram bin width is 8 kHz.

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In this work we experimentally investigate the effect of individual nuclear spins on the operation of a double quantum dot device (Fig. 1c), which was characterized previously in ref. 20. Quantum dots QD1 and QD2 can be completely emptied, and single electrons can be loaded from the nearby electron reservoir. Application of an external magnetic field $B_{ext}=1.42 \pm 0.04$ T to split the electron spin eigenstates by 39 GHz allows spin readout via the spin-selective unloading20 of an electron from QD2. Furthermore, a single electron can be transferred between QD1 and QD2, while maintaining its spin polarization16,20. Electron spin resonance (ESR) pulses applied to an on-chip microwave antenna allow coherent manipulations of the electron spin, with intrinsic spin transition linewidths around 50 kHz (ref. 8). When monitoring the spin resonance frequency ($f_e$) for an electron loaded in QD1 (with QD2 empty) over extended periods of time, discrete jumps can be observed (Fig. 1d, left). Indeed, the histogram in Fig. 1d (right) suggests the presence of two distinct two-level systems, resulting in shifts in $f_e$ of ~120 kHz and 450 kHz.

To determine whether the two-level fluctuations can be attributed to $^{29}$Si nuclear spins, we focus our attention on the 450 kHz shift. We first apply a radiofrequency (RF) tone with QD1 unloaded, and then check whether the ESR frequency has shifted by repeatedly probing the electron spin inversion probability around $f_e$. The hyperfine interaction causes each frequency to be affected by the diagram’s recording sweep rate. Energy levels of the joint electron–nuclear spin system, for a single nuclear spin coupled to QD1, can be loaded from the nearby electron reservoir. Application of a spin-down electron, we find the NMR frequency has shifted to $f_{n} = f_e + |A|/2$ (Fig. 2f, right peak), yielding an accurate measurement of $A = -448.5 \pm 0.1$ kHz at this control point. Finally, we repeat the experiment once more, where we load QD1 with an electron with spin up (by applying adiabatic ESR inversion, see Methods), and confirm $f_{n} = f_e - |A|/2$ (Fig. 2f, left peak). In Extended Data Fig. 3 we present results for another $^{29}$Si nuclear spin coupled to the

$$ H = -B_{ext}(\gamma_e S_z + \gamma_n I_z) + A(S \cdot I) $$

where $S$ and $I$ are the electron and $^{29}$Si spin operators and $\gamma_n = -28$ GHz T$^{-1}$ is the electron gyromagnetic ratio. Here, the interaction is dominated by the contact hyperfine term, with dipole-dipole terms expected to be several orders of magnitude smaller25. The Hamiltonian results in the energy eigenstates shown in Fig. 2b, with both electron and nuclear spin transitions splitting by $A$ when the electron is loaded onto QD1. Repeating the same experiment as above, but applying NMR pulses after loading QD1 with a spin-down electron, we find the NMR frequency has shifted to $f_{n} = f_e + |A|/2$ (Fig. 2f, right peak), yielding an accurate measurement of $A = -448.5 \pm 0.1$ kHz at this control point. Finally, we repeat the experiment once more, where we load QD1 with an electron, and obtain $f_{n} = f_e - |A|/2$ (Fig. 2f, left peak). In Extended Data Fig. 3 we present results for another $^{29}$Si nuclear spin coupled to the...
electron spin in QD2 that has hyperfine $A_{QD2} = -179.8 \pm 0.2$ kHz. Electrostatic modelling based on the device gate geometry indicates an electron wavefunction diameter of ~8 nm, which is consistent with the hyperfine couplings observed in QD2; however, the coupling observed for the $^{28}$Si in QD1, while possible for a diameter of 7 nm, suggests that an additional disorder potential may have reduced the size of this dot wavefunction.

Having confirmed the ability to controllably address individual nuclear spins, we proceed to characterize a qubit encoded in this new resource. As observed from the interval between jumps in Fig. 1b, the nuclear spin lifetime extends to tens of minutes, despite repeatedly probing the electron resonance frequency, a process that probably increases the spin flip rate. By fitting an exponential decay to the intervals between the 450 kHz and 120 kHz jumps for the data in Fig. 1b, we find $T_1^{\text{450kHz}} = 1.0 \pm 0.5$ s and $T_1^{\text{120kHz}} = 10.0 \pm 0.6$ min (see Supplementary Fig. 1 for details). This means we can perform multiple quantum non-demolition measurements of the nuclear spin state to boost the nuclear spin state readout fidelity $^{\text{X}}$. A simple simulation (see Methods) for $M$ repeated readouts, taking into account the 8 ms measurement cycle and the electron spin readout visibility of 76%, results in an optimal number of readouts of $M_{\text{opt}} = 26$, and an obtainable nuclear spin readout fidelity of 99.99%. In this work we limit $M$ to 20, resulting in a measured nuclear spin readout fidelity of 99.8% for the dataset in Fig. 3 (see Methods for details). We determine the nuclear spin coherence times by performing nuclear Ramsey and Hahn-echo sequences, with the electron unloaded (see Fig. 2g,i) as well as Extended Data Fig. 2 for data in the (0,0) charge state) and loaded (Fig. 2h,i). We find nuclear coherence times between two and three orders of magnitude longer than those measured for the electron in this device ($T_1 \approx 15$ μs; ref. 8), but shorter than previously measured for nuclear spins coupled to donors in enriched silicon$^5$. Possible explanations include the closer proximity of the device surface, as well as statistical variation in placement of neighbouring nuclei. Remarkably, the ratio between Hahn times $T_2^{\text{Hahn,unloaded}}$ and $T_2^{\text{Hahn,loaded}}$ is only a factor of order unity, compared to three orders of magnitude for an ionized phosphorus donor in silicon$^5$.

In the present case, the bath of resonant $^{28}$Si nuclei in the unloaded device may affect the measured coherence times. A full overview of the measured coherence times is presented in Extended Data Fig. 5. In Supplementary Note 1, we discuss possible sources of dephasing resulting in the measured coherence times.

In Fig. 3, we use coherent control to prepare entangled states of the joint electron–nuclear two-qubit system. We perform all operations with the electron loaded and construct the required unconditional rotations from two consecutive conditional rotations$^7$ (Fig. 3a,b). After careful calibration of the a.c. Stark shifts induced by the off-resonant conditional ESP pulses (Fig. 3c,d), we characterize the prepared Bell state fidelity by measuring the two-qubit expectation values $\langle XX \rangle$, $\langle YY \rangle$ and $\langle ZZ \rangle$ of the joint $x,y,z$-Pauli operator on the nucleus and electron, respectively. We correct the two-qubit readout probabilities for final electron readout errors only, which we calibrate by interleaving the entanglement measurement with readout fidelity characterizations (see Methods). Note that, because the nuclear spin is initialized by measurement here, we obtain an identical dataset corresponding to initial nuclear state $|\Psi \rangle$, which we show in Extended Data Fig. 4. We find an average Bell state preparation fidelity of 73.0 ± 1.9%.

Our entanglement protocol is affected by several errors. By performing a numerical time-domain evolution simulation of our protocol (see Methods for details), we estimate the effects of various noise sources on the nuclear–electron Bell state fidelity. We find that the dominant source of error is the electron $T_1$ ($\approx 10$ s), followed by the uncontrolled 120 kHz coupled $^{28}$Si nucleus, observed in Fig. 1b (5%). Depending on the state of this nuclear spin, depolarizing ESP pulses cause an unknown phase shift. Other contributions include pulse duration calibration errors (~2%) and the reduced NMR control fidelity with QD1 loaded (3%).

A unique feature of our quantum-dot-coupled nuclear spin qubit is the large ratio of interdot tunnel coupling $T_1$ to hyperfine coupling $A$, so that $|I_n| \gg |A| \gg 1/T_1$, with $|I_n|$ on the order of 1 GHz in this device$^6$. We should therefore be able to accurately and adiabatically control the movement of an electron charge between neighbouring
The nuclear phase preservation raises the prospect to entangle nuclei in separate quantum dots, mediated by the electron shuttling. For that to work, the electron spin state itself must also remain coherent during transfer. By performing an electron Ramsey experiment, where the first \( \pi/2 \) pulse is driven with the electron in QD1 and the second \( \pi/2 \) pulse is driven with the electron in QD2 (Fig. 4e,f), we demonstrate that electrons do indeed preserve coherence, presently with modest transfer fidelities.

The readout and control of nuclear spins coupled to quantum dots shown here presents us with a variety of future research possibilities. First, the nuclear spin qubits could form the basis for a large-scale quantum processor, where initialization, readout and multi-qubit interactions are mediated by electron spins. Second, the nuclear spin qubits could be used as a quantum memory in an electron spin-based quantum processor. Implementations of quantum error correcting codes may benefit from integrated, long-term quantum state storage. In particular, lossy or slow long-range interactions between quantum dots, for example mediated by microwave photonic qubits, could be admissible if supplemented by local nuclear spin resources for memory or purification. Finally, the nuclear spin qubits can be used as a characterization tool for electron spin-based qubits. For example, in the present experiment, the confirmed existence of a nucleus with 450 kHz hyperfine coupling bounds the electron waveform diameter to under 8 nm, a conclusion difficult to draw with purely electrostatic calculations or electronic measurements. Further characterizations of electron spin dynamics may be envisioned by mapping the electron spin state to the nuclear spin, and employing the nucleus as a high-fidelity readout tool.

Limitations include the extended control times for the nuclear spin, as well as the effects of long NMR pulses on electron spin readout (Supplementary Note 2). Both limitations could be addressed by redesigning the RF delivery, for example using a global RF cavity. Individual nuclei in a specific quantum dot could then be targeted by either loading or unloading the electron on that dot, and addressing the hyperfine shifted Larmor frequency. Presently, the \(^{29}\)Si are randomly distributed, resulting in a range of hyperfine couplings for each quantum dot. Although the probability of obtaining at least one addressable \(^{29}\)Si per quantum dot is large (Extended Data Fig. 1), implantation of \(^{29}\)Si nuclei in (possibly further enriched) silicon host material would allow the design of an optimal interaction. This could be done via ion implantation, requiring a relatively modest precision on the order of the size of the quantum dots, which is much more forgiving than the precision needed for direct

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**Fig. 4 | Nuclear and electron spin coherence during electron transfer.** a, We verify that the nuclear spin coherence is maintained when moving the electron from quantum dot QD2 to QD1, by performing a non-detuned nuclear Ramsey experiment where we load the electron onto QD1 for a time \( t_{\text{load}} \) during free precession, while keeping the total precession time \( t_r \) constant. b, With QD1 loaded the nuclear phase evolution is altered relative to the bare rotating frame by the hyperfine interaction, directly observable by the phase evolution as a function of \( t_{\text{load}} \) (keeping \( t_r = 0.5 \) ms). The sinusoidal oscillation frequency (fitted, solid line) yields another measurement for \( |A|/2 \). The oscillation visibility is limited by the electron spin initialization fidelity (for electron spin-\( 1 \) the oscillations have opposite phase). c, By repeatedly loading and unloading the electron we can estimate the loss of coherence due to the loading process. d, Bottom: to quantify the retained nuclear spin coherence independent of deterministic phase shifts we measure the probability \( P_{\text{flip}} \) of the nuclear spin state being in the states \( X, -X, Y, -Y \) corresponding to a spin-up result after the final Ramsey pulse phases \( \phi \) of 0°, 180°, 90° and 270°. Top, nuclear coherence \( C = \sqrt{\langle (P_x - P_{-x})^2 + (P_y - P_{-y})^2 \rangle} \). Treating the loading/unloading process as a dephasing channel, we fit an error probability per load/unload cycle of 0.45 ± 0.29% (solid line; see Methods). Here, \( t_r = 1.25 \) ms is fixed. e, In an analogous measurement, we verify that the electron spin coherence is maintained while shuttling it from QD1 to QD2, by performing an electron Ramsey where the first pulse is driven with the electron in QD1, and the second pulse with the electron in QD2. Note that, because of the \( g \)-factor difference between quantum dots QD1 and QD2, the second pulse has a different frequency \( f_{\text{QD2}} \). The nuclear spin state remains fixed in this experiment. f, Electron spin-\( 1 \) readout probability as a function of final Ramsey phase \( \phi \) and shuttling ramp time \( t_{\text{ramp}} \) showing a coherent spin transfer, with -30% visibility (no correction for readout).
donor–donor coupling. Finally, in a scaled computational architecture, quantum dots without a controllable nuclear spin could be worked around by adapting the electron shuttling protocol, or the used error correction code.

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Methods

Experimental methods. Details of sample fabrication and the experimental set-up are available in ref. 39. NMR pulses were generated by a secondary microwave vector signal generator and combined with the ESR pulses using a resistive combiner. Conditioned ESR pulses for nuclear readout were generated via adiabatic inversions with a frequency span of $f_1 = 300$ kHz to $f_3 = 50$ kHz and $f_4 = 50$ kHz to $f_6 = 300$ kHz for reading nuclear spins $\uparrow$, $\downarrow$, respectively. The adiabatic pulse had a duration of 650 $\mu$s and a power corresponding to a 100 kHz Rabi frequency.

Electron spin transfers between QD1 and QD2 were performed with a 1 $\mu$s linear ramp, except where indicated otherwise.

Nuclear spin readout fidelity. We modelled the repetitive nuclear readout as a stochastic process, where, as a function of the number of shots $M$, the fidelity on the one hand is limited by the nuclear $T_1$ decay:

$$F_N = \exp(-2M\text{d}_{\text{shot}}/T_1)$$

with $\text{d}_{\text{shot}}$ = 8 ms being the measurement time per shot, $T_1 = 1$ h, and the factor 2 comes from the fact that for each shot we read out the electron twice, once for an inversion around $f_3$ and once for $f_7$.

On the other hand the fidelity is limited by the cumulative binomial distribution representing the majority voting of $M$ single shots:

$$F_N = \frac{1}{M} \sum_{k=0}^{M} \binom{M}{k} \left(1 - F_{\text{d}}\right)^k \left(F_{\text{d}}\right)^{M-k}$$

A first-order estimate for the nuclear readout is then obtained by

$$F_N = \left(1 - F_e\right)F_{\text{shot}} + F_e \left(1 - F_{\text{mis}}\right)$$

resulting in a minimum infidelity of $1 - F_e = 10^{-6}$ for $M_e = 26$, for $F_{\text{mis}} = 76.5\%$, where we have taken the average electron spin readout fidelity recorded for the dataset in Fig. 3e.

Nuclear–electron entanglement experimental details. For the datasets presented in Fig. 3e and Extended Data Fig. 4e, we interleave the following measurement sequences:

1. Bell state preparation + (ZZ) projection
2. Bell state preparation + (XX) projection
3. Bell state preparation + (YY) projection
4. Electron spin-↑ readout characterization for (ZZ) projection
5. Electron spin-↑ readout characterization for (ZZ) projection
6. Electron spin-↓ readout characterization for (XX) and (YY) projection
7. Electron spin-↓ readout characterization for (XX) and (YY) projection

Before running each sequence, we initialized the electron spin state to $|\uparrow\rangle$, using a spin relaxation hotspot at the (0.13–0.17) charge transition (for details see ref. 39). After running a sequence once, we read the state of both electron and nuclear spin (corresponding to a total of 2M+1 electron spin readouts). We then performed an ESR frequency check and, if necessary, calibration. The frequency check proceeded by applying a weak, resonant ESR pulse (60 kHz Rabi frequency), and failed if the spin inversion probability dropped below 0.8. If the check failed for both $f_5$ and $f_7$, the ESR frequency was recalibrated using a series of Ramsey sequences to estimate the detuning. Details of this ESR frequency calibration are described in the supplementary information of ref. 39. After recording 10 data points of sequence 1 in this manner, we switch to sequence 2, and so on. After sequence 7 we loop back to sequence 1, until the end of the measurement. The nuclear spin initialization is given by the readout result in the previous sequence. The total measurement time for the presented dataset was 9.5 h, resulting in 4,320 Bell state preparations.

The aim of sequences 4–7 is to record the actual average electron spin readout fidelity while recording the dataset. To estimate the spin-↑ readout fidelity (sequences 4 and 6), we apply no ESR pulses and measure the spin-↑ readout probability. To estimate the spin-↓ readout fidelity we apply an adiabatic inversion of the electron spin, consisting of a 650 $\mu$s-long 2.8 MHz-wide frequency sweep centred around $f_5$, with a power corresponding to a 100 kHz Rabi frequency, and measure the spin-↑ readout probability. Sequences 4 and 5 each have the same NMR pulses applied as sequence 1, but applied far detuned to mimic the effect of the (ZZ)-projection NMR pulse on the electron spin readout fidelity, while not changing the nuclear spin state itself. Similarly, sequences 6 and 7 have the same NMR pulses as sequence 2, but far detuned to mimic the effect of (XX), (YY)-projection pulses. For the (ZZ)-projection we find readout fidelities of $F_{\text{zz}}$ = 88.4% and $F_{\text{zz}}$ = 73.3%, while for the (XX), (YY)-projection we find $F_{\text{xx}}$ = 80.7% and $F_{\text{xx}}$ = 67.4%.

Finally, data from sequences 4–7 are also used to obtain an estimate for the nuclear spin readout fidelity; because all NMR pulses are applied off resonance, the nuclear spin should remain unchanged. If the nuclear spin is read out differently after running sequences 4–7, this indicates a readout error has occurred. We found five readout errors in 3,200 nuclear spin readouts, identified as such by a single outcome being different in a sequence of 10. The readout fidelity is estimated as the fraction of readout errors.

The bar plots shown in Fig. 3e and Extended Data Fig. 4c are corrected using their respective electron spin readout fidelity characterization, using direct inversion. We estimate the Bell state fidelity using $F = F_{\text{zz}}(1/2 + P_{\text{err}}) = 1/2 + P_{\text{err}}$, where $F_{\text{zz}}$, $P_{\text{err}}$, $P_{\text{err}}$, $F_{\text{zz}}$, $F_{\text{zz}}$, and $P_{\text{err}}$, for nuclear spin-↓ initialized data (Fig. 3e) and $F_{\text{zz}}$, $P_{\text{err}}$, $F_{\text{zz}}$, $P_{\text{err}}$, $F_{\text{zz}}$, and $P_{\text{err}}$, for nuclear spin-↑ initialized data (Extended Data Fig. 4c).

Nuclear-electron entanglement error analysis. Using the two-spin Hamiltonian, equation (1), with two control fields $V_{\text{c1}} = |e\rangle\langle b|/0.5$, and $V_{\text{c2}} = |e\rangle\langle b|/2.6$, and taking the secular and rotating wave approximation, we perform a time evolution simulation to estimate the effects of various noise sources on the nuclear–electron Bell state fidelity. We simulate the exact control sequences $B(t)$ used in the experiment. The simulation calculates the operator at any specific time $U(t) = \exp(-iH_{\text{elec}}t)$, where $H_{\text{elec}}$ incorporates quasi-static noise along $J$, $I$, and $S$ directions following a Gaussian distribution with standard deviations of $\Delta f_{\text{z}} = 120$ kHz, $\Delta f_{\text{x}} = 1.1$ ms, $T_1 = 1.1$ ms, $T_2 = 2.9$ ms, and $T_2^* = 15$ ms. The value for $T_2^*$ has a large uncertainty, ranging from 8 to 22 $\mu$s depending on the exact ESR frequency feedback settings and interval39. To simulate the effect of the uncontrolled 120 kHz coupled $^3$Si spin, we estimate the probability that the nuclear spin flips within the time of ESR frequency checks, resulting in an unnoticed frequency shift. Using $T_{\text{z}}(\text{unobs}) = 10$ min, and an average time between ESR frequency checks of 40 s, we find a probability of 7% of running the entanglement sequence with 120 kHz detuned ESR pulses. Finally, to simulate the effect of pulse calibration errors, we estimate our pulse-length calibration is accurate within 5%. Error percentages quoted in the main text are the reduction in final Bell state fidelity resulting from incorporating the corresponding error mechanism only, with all other error mechanisms turned off in the simulation.

Coherent loading dephasing analysis. We model the effect of transferring the electron between QD1 and QD2 on the nuclear spin state as a dephasing channel

$$\rho = \left(\begin{array}{cccc} f_{\text{nuc}} & 0 & 0 & 0 \\ 0 & f_{\text{nuc}} & 0 & 0 \\ 0 & 0 & f_{\text{nuc}} & 0 \\ 0 & 0 & 0 & f_{\text{nuc}} \end{array}\right)$$

This model yields an exponentially decaying off-diagonal matrix element magnitude as a function of channel transfers $k$, $|\langle k+1|\rangle = 1/2\exp(-k\gamma f_{\text{nuc}}) = 1/2\exp(-kT_\gamma)$, which is measured coherence defined in the caption of Fig. 4d.e.

Data availability

The data that support the plots within this paper and other findings of this study are available from the corresponding authors upon reasonable request.

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Author contributions

B.H. and WWH performed the experiments. K.W.C. and F.E.H. fabricated the devices. K.M.I. prepared and supplied the $^3$Si wafer. B.H., WWH, C.-H.Y., J.T., T.T. and A.L designed the experiments. B.H., WWH, and J.Y. analysed the data. T.D.L. performed hyperfine and coherence simulations. B.H. wrote the manuscript with input from all co-authors. A.M., A.L. and A.S.D. supervised the project.

Competing interests

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Additional information

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Extended Data Fig. 1 | Expected hyperfine interaction. a, Maximum possible hyperfine interaction for given dot diameter, defined as the 1/e point of the envelope charge distribution, and vertical confining electric field $F_z$. b, Probability of observing at least one nuclear spin with hyperfine coupling $|\Delta| \geq 100$ kHz (dashed line), $|\Delta| \geq 200$ kHz (solid line) and $|\Delta| \geq 500$ kHz (dotted line), for 800 ppm $^{29}$Si material. These distributions are found by calculating the electron wavefunction density for an Airy envelope function, sinusoidally oscillating in the vertical dimension due to valley oscillations, and with a transverse Gaussian shape, all superimposed over an unstrained silicon lattice. We assume $^{29}$Si are randomly placed with 800 ppm probability at each lattice site and evaluate the resulting hyperfine contact interaction. The probabilities grow with dot diameter due to increased number of sites overlapped, but then shrink for large dots due the reducing hyperfine contact at each site.
Extended Data Fig. 2 | Ramsey and Hahn echo measurement in the (0,0) charge state. a, Ramsey measurement and b, Hahn echo measurement with nuclear pulses and free evolution time in charge configuration (0,0). Resulting values $T_2^{(0,0)} = 6.0 \pm 0.6$ ms and $T_2^{\text{Hahn,(0,0)}} = 13.1 \pm 1.5$ ms are within error to those obtained for the unloaded-(0,1) charge configuration, see Fig. 2g, i.
Extended Data Fig. 3 | Second $^{29}$Si qubit coupled to quantum dot QD2. a, NMR frequency scan with QD2 loaded with a spin-$\downarrow$ electron, charge configuration (0,1), reveals a $^{29}$Si nuclear spin coupled by $A_{\text{QD2}} = -179.8 \pm 0.2$ kHz. Note that the nuclear spin readout contrast is reduced due to the small hyperfine splitting. b, Loaded Ramsey measurement yields $T_2^{\text{loaded}} = 21 \pm 5$ ms, for 1 hour integration time. c, Loaded Hahn echo measurement yields $T_2^{\text{Hahn, loaded}} = 42 \pm 11$ ms. d, Unloaded, charge state (0,0), Hahn echo yields $T_2^{\text{Hahn,(0,0)}} = 40 \pm 13$ ms.
Extended Data Fig. 4 | Nuclear-electron entanglement data for opposite nuclear spin initialization. **a, b.** As expected, for a nuclear spin-\(\uparrow\)-initialised state, varying the nuclear and electron projection phases \(\phi_n, \phi_e\) respectively, we observe oscillations with opposite phase compared to those for a nuclear spin-\(\downarrow\)-initialised state, compare Fig. 3c, d. **c.** Accordingly, XX and YY projections have opposite parity, compare Fig. 3e.
### Extended Data Fig. 5 | Overview of nuclear coherence times

Details and fitted values for all Ramsey and Hahn echo sequences performed on two $^{29}\text{Si}$ nuclear spins, one in quantum dot QD1, one in QD2, for different charge states. Ramsey values are fits to a sinusoidal function with envelope decay $-\exp[-(\tau/\tau_2^*)]$. Int. time indicates total integration time for the measurement. Hahn echo values are fits to an exponential decay $-\exp(-2\tau/\tau_{2\text{Hahn}})$. Figure panels displaying each measurement are indicated. Note that for the $\tau_2^*$-values given in the captions of Fig. 2 and Extended Data Figs. 2,3, the integration times are all limited to 1 hour, for comparison.

| Nuclear spin in quantum dot | Charge state | Hyperfine magnitude | Ramsey $\tau_2^*$ | Exponent $\alpha$ | Int. time | Figure | Hahn echo $\tau_{2\text{Hahn}}$ | Figure |
|-----------------------------|--------------|---------------------|-----------------|----------------|-----------|--------|-------------------------------|--------|
| QD1 (0,1) - unloaded        | 450 kHz      | 6.6 ± 0.2 ms        | 2.11 ± 0.21     | 3.2 hrs        | Fig. 2g   | 16.3 ± 2.4 ms                  | Fig. 2i |
| QD1 (1,0) - loaded          | 450 kHz      | 2.9 ± 0.7 ms        | 0.91 ± 0.25     | 1.1 hrs        | Fig. 2h   | 22.8 ± 4.1 ms                  | Fig. 2j |
| QD1 (0,0) - unloaded        | 450 kHz      | 5.9 ± 0.2 ms        | 1.54 ± 0.39     | 7 hrs          | Ext. 2a   | 13.1 ± 1.5 ms                  | Ext. 2b |
| QD2 (0,1) - loaded          | 180 kHz      | 21.3 ± 2.0 ms       | 1.74 ± 0.16     | 6.3 hrs        | Ext. 3b   | 42.2 ± 10.6 ms                 | Ext. 3c |
| QD2 (0,0) - unloaded        | 180 kHz      | Not measured        |                 |               |           | 40.5 ± 13.0 ms                 | Ext. 3d |