DNP in Quantum Computing

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2017.08.25

Future of Hyper-Polarized Nuclear Spins

@IPR, Osaka

DNP in quantum computing

- **Molecule**
  - Pseudo-pure state
  - Algorithmic cooling
- **Phosphorus donor in silicon**
  - ENDOR
  - Single nuclear spin under control

DiVincenzo's criteria

1. A scalable physical system with well characterized qubits

   Spin-½

2. The ability to initialize the state of the qubits to a simple fiducial state, such as |000...⟩

3. Long relevant decoherence times, much longer than the gate operation time

4. A "universal" set of quantum gates

5. A qubit-specific measurement capability

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Fortschr. Phys. **48**, 771 (2000) DiVincenzo

DiVincenzo's criteria

1. A scalable physical system with well characterized qubits
   Spin-½
2. **The ability to initialize the state of the qubits to a simple fiducial state, such as |000...⟩ → 100% DNP**
3. Long relevant decoherence times, much longer than the gate operation time T_2
4. A "universal" set of quantum gates
   Arbitrary unitary operations
5. A qubit-specific measurement capability

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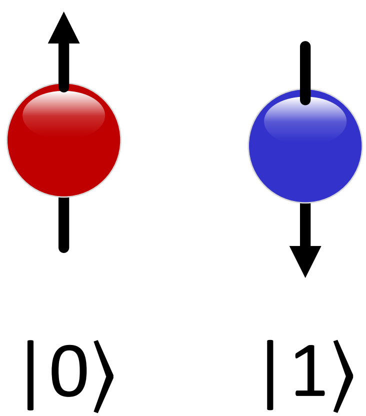
Fortschr. Phys. **48**, 771 (2000) DiVincenzo

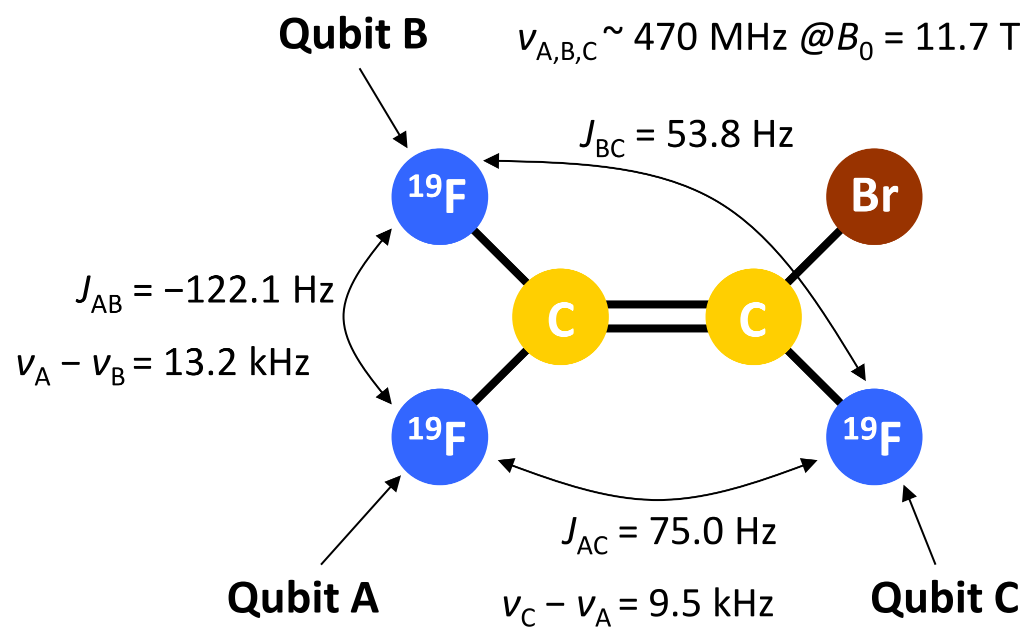
A molecule as a quantum computer

Hamiltonian

$$H_{\mathrm{mol}} = -\sum_{i} \nu_i I_z^i + \sum_{i<j} J_{ij} I_z^i I_z^j$$



Bromotrifluoroethylene



A molecule as a quantum computer

Hamiltonian

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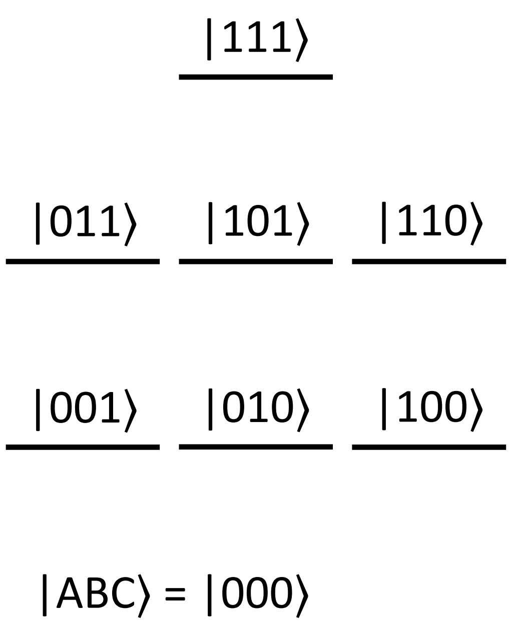
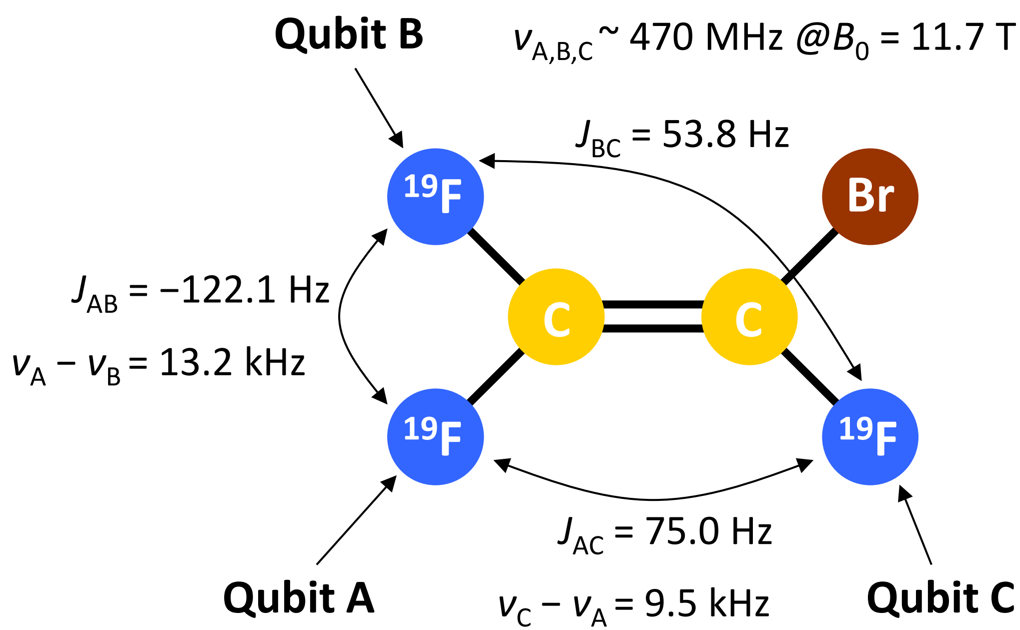


Bromotrifluoroethylene



DiVincenzo’s criteria for a molecule

1. Qubits: Nuclear spins in a molecule → $(ABC)_n$ polymer*
2. Initialization: “**Measure and flip**”
3. Coherence: Good
4. Quantum gates: RF control and spin-spin interaction (always on)
5. Measurement: ✕

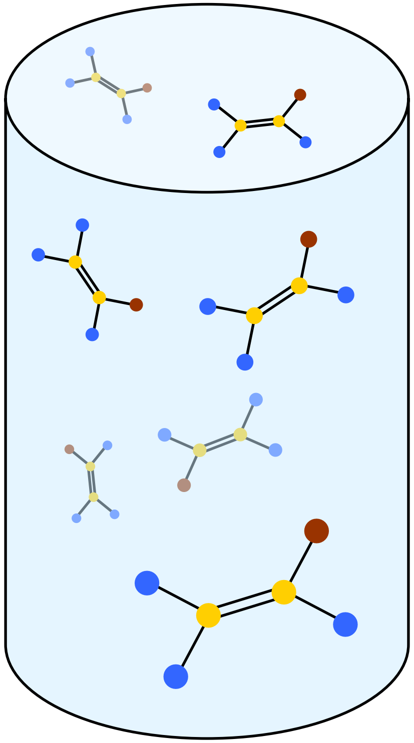
*Science **261**, 1569 (1993) Lloyd

Molecules as a quantum computer

Hamiltonian

$$H_{\mathrm{mol}} = -\sum_i \nu_i I_z^i + \sum_{i<j} J_{ij} I_z^i I_z^j$$

Ensemble of molecules can be measured, but then how to initialize them?



Thermal equilibrium ensemble

(> 10^{18} identical molecules)

Spin system in thermal equilibrium

Hamiltonian

$$H_{\mathrm{mol}} = -\sum_i \nu_i I_z^i + \sum_{i<j} J_{ij} I_z^i I_z^j \approx -\nu_0 \sum_i I_z^i$$

Density matrix

$$\rho_{\mathrm{eq}} = \frac{1}{Z}\exp\left(-\frac{H_{\mathrm{mol}}}{k_{\mathrm{B}}T}\right) \approx \boxed{\frac{\mathbf{1}_n}{2^n}} + \frac{\epsilon}{2^n}\rho_n$$

Silent majority (no signal, no time evolution)

$$\epsilon = \frac{500\ \mathrm{MHz}}{2 \times 300\ \mathrm{K}} \approx 10^{-5}$$

$$\rho_n = \sum_i \sigma_z^i \quad \begin{cases} \rho_1 = \sigma_z \\ \rho_2 = \sigma_z \otimes \mathbf{1}_1 + \mathbf{1}_1 \otimes \sigma_z \\ \rho_3 = \sigma_z \otimes \mathbf{1}_1 \otimes \mathbf{1}_1 + \mathbf{1}_1 \otimes \sigma_z \otimes \mathbf{1}_1 + \mathbf{1}_1 \otimes \mathbf{1}_1 \otimes \sigma_z \end{cases}$$

Simplified notation of ρ_n

$$d(\rho_1) = \begin{pmatrix} 1 \\ -1 \end{pmatrix} \begin{matrix} |0\rangle \\ |1\rangle \end{matrix}$$

$$d(\rho_2) = \begin{pmatrix} 2 \\ 0 \\ 0 \\ -2 \end{pmatrix} \begin{matrix} |00\rangle \\ |01\rangle \\ |10\rangle \\ |11\rangle \end{matrix}$$

$$d(\rho_3) = \begin{pmatrix} 3 \\ 1 \\ 1 \\ -1 \\ 1 \\ -1 \\ -1 \\ -3 \end{pmatrix} \begin{matrix} |000\rangle \\ |001\rangle \\ |010\rangle \\ |011\rangle \\ |100\rangle \\ |101\rangle \\ |110\rangle \\ |111\rangle \end{matrix}$$

Initialization

Thermal equilibrium

$$\rho_{\mathrm{eq}} = \frac{\mathbf{1}_n}{2^n} + \frac{\epsilon}{2^n}\rho_n$$

$$\rho_{\mathrm{pure}} = |000\ldots\rangle\langle 000\ldots|$$

100% DNP

$$d(\rho_{\mathrm{pure}}) = \begin{pmatrix} 1 \\ 0 \\ \vdots \\ 0 \end{pmatrix}$$

$$\rho_{\mathrm{pps}} = (1-\alpha)\frac{\mathbf{1}_n}{2^n} + \alpha\rho_{\mathrm{pure}}$$

Pseudo-pure state

- Temporal averaging
- Spatial averaging
- **Logical labeling**

RESEARCH ARTICLES

Bulk Spin-Resonance Quantum Computation

Neil A. Gershenfeld and Isaac L. Chuang*

Science **275**, 350 (1997) Gershenfeld & Chuang

(©MIT)

(©IQC, U. Waterloo)

Ensemble quantum computing by NMR spectroscopy

(NMR/quantum computing/DNA computing/nondeterministic polynomial-time complete)

David G. Cory‡, Amr F. Fahmy§, and Timothy F. Havel§¶

‡Department of Nuclear Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139; and §Biological Chemistry and Molecular Pharmacology, Harvard Medical School, Boston, MA 02115

PNAS **94**, 1634 (1997) Cory *et al.*

Experimental Implementation of Fast Quantum Searching

Phys. Rev. Lett. **80**, 3408 (1998) Chuang *et al.*

(Received **21 Nov. '97**; published **13 Apr.**)

Isaac L. Chuang,[1,*] Neil Gershenfeld,[2] and Mark Kubinec[3]
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[2] *Physics and Media Group, MIT Media Lab, Cambridge, Massachusetts 02139*
[3] *College of Chemistry, D7 Latimer Hall, University of California, Berkeley, Berkeley, California 94720-1460*

Experimental realization of a quantum algorithm

Isaac L. Chuang*, Lieven M. K. Vandersypen†, Xinlan Zhou†, Debbie W. Leung‡ & Seth Lloyd§

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† *Solid State and Photonics Laboratory, Stanford University, Stanford, California 94305, USA*
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§ *MIT Department of Mechanical Engineering, Cambridge, Massachusetts 02139, USA*

Nature **393**, 143 (1998) Chuang *et al.*

(Received **21 Jan.**; accepted **18 Mar.**; published **14 May**)

Implementation of a quantum search algorithm on a quantum computer

Jonathan A. Jones*†, Michele Mosca†‡ & Rasmus H. Hansen†

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† *Centre for Quantum Computation, Clarendon Laboratory, Parks Road, Oxford OX1 3PU, UK*
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Nature **393**, 344 (1998) Jones *et al.*

(Received **6 Mar.**; accepted **23 Apr.**; published **28 May**)

Implementation of a quantum algorithm on a nuclear magnetic resonance quantum computer

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Centre for Quantum Computation, Clarendon Laboratory, Parks Road, Oxford OX1 3PU, United Kingdom and Mathematical Institute, 24-29 St Giles', Oxford, OX1 3LB, United Kingdom

J. Chem. Phys. **109**, 1648 (1998) Jones *et al.*

(Received **16 Jan.**; accepted **22 Apr.**; published **1 Aug.**)

Experimental realization of Shor's quantum factoring algorithm using nuclear magnetic resonance

Lieven M. K. Vandersypen*†, Matthias Steffen*†, Gregory Breyta*, Costantino S. Yannoni*, Mark H. Sherwood* & Isaac L. Chuang*†

** IBM Almaden Research Center, San Jose, California 95120, USA*
† Solid State and Photonics Laboratory, Stanford University, Stanford, California 94305-4075, USA

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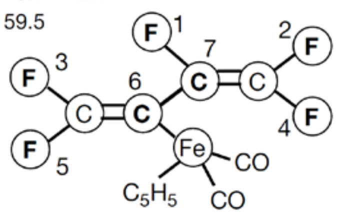
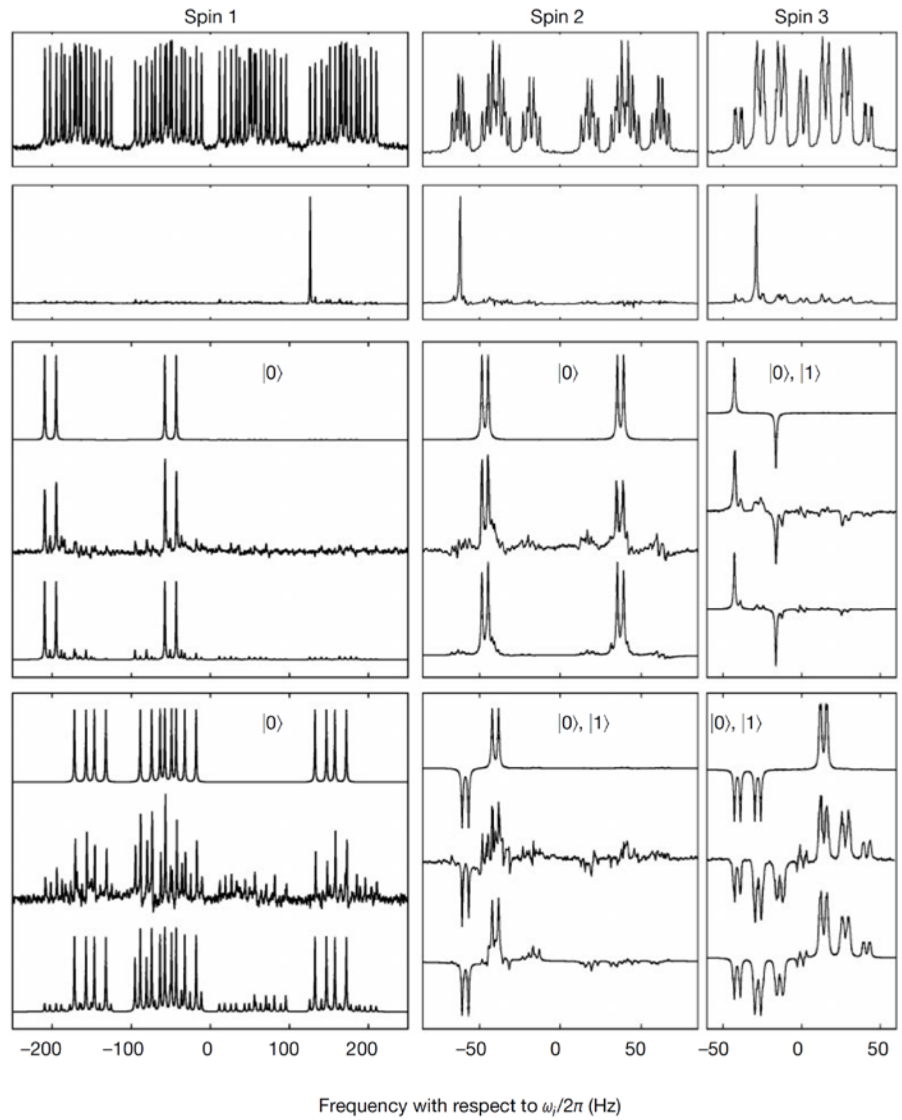
i	$\omega_i/2\pi$	$T_{1,i}$	$T_{2,i}$	J_{7i}	J_{6i}	J_{5i}	J_{4i}	J_{3i}	J_{2i}
1	−22052.0	5.0	1.3	−221.0	37.7	6.6	−114.3	14.5	25.16
2	489.5	13.7	1.8	18.6	−3.9	2.5	79.9	3.9	
3	25088.3	3.0	2.5	1.0	−13.5	41.6	12.9		
4	−4918.7	10.0	1.7	54.1	−5.7	2.1			
5	15186.6	2.8	1.8	19.4	59.5				
6	−4519.1	45.4	2.0	68.9					
7	4244.3	31.6	2.0						





Nature **414**, 883 (2001) Vandersypen *et al.*

DiVincenzo's criteria for NMR QC

1. Qubits: Nuclear spins in molecules → $(ABC)_n$ polymers*
2. Initialization: DNP, **pseudo-pure state**, **algorithmic cooling****
3. Coherence: Good
4. Quantum gates: RF control and spin-spin interaction (always on)
5. Measurement: **Ensemble-averaged signals**

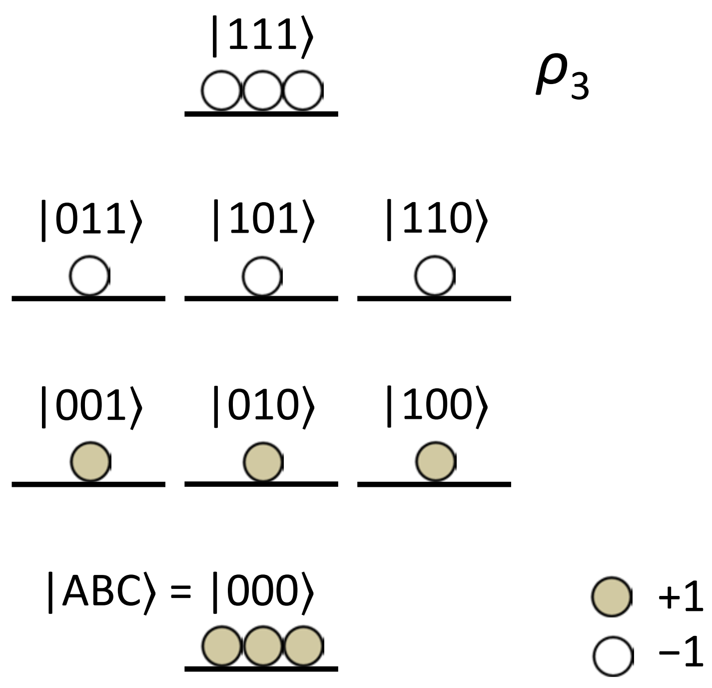
*Science **261**, 1569 (1993) Lloyd

**Proc. 31st Annu. ACM Symp. Theory Compt. p.322 (1999) Schulman & Vazirani

Logical labeling

Case study: *n* = 3

$$d(\rho_3) = \begin{pmatrix} 3 \\ 1 \\ 1 \\ -1 \\ 1 \\ -1 \\ -1 \\ -3 \end{pmatrix}$$



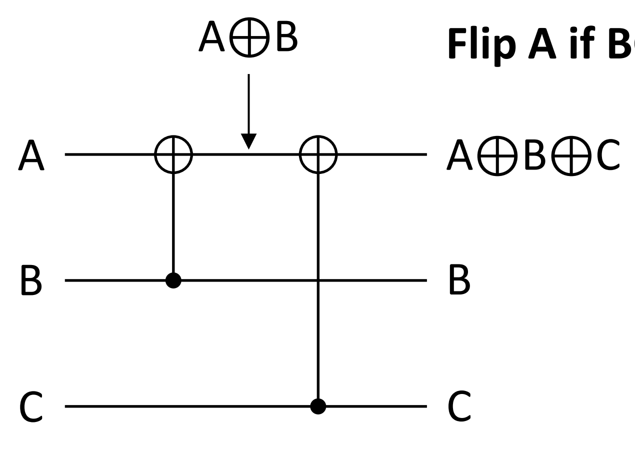
Logical labeling

Case study: *n* = 3

$$d(\rho_3) = \begin{pmatrix} 3 \\ 1 \\ 1 \\ -1 \\ 1 \\ -1 \\ -1 \\ -3 \end{pmatrix}$$

Unitary operator for LL_3

$$V = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$



Flip A if BC = 01 or 10

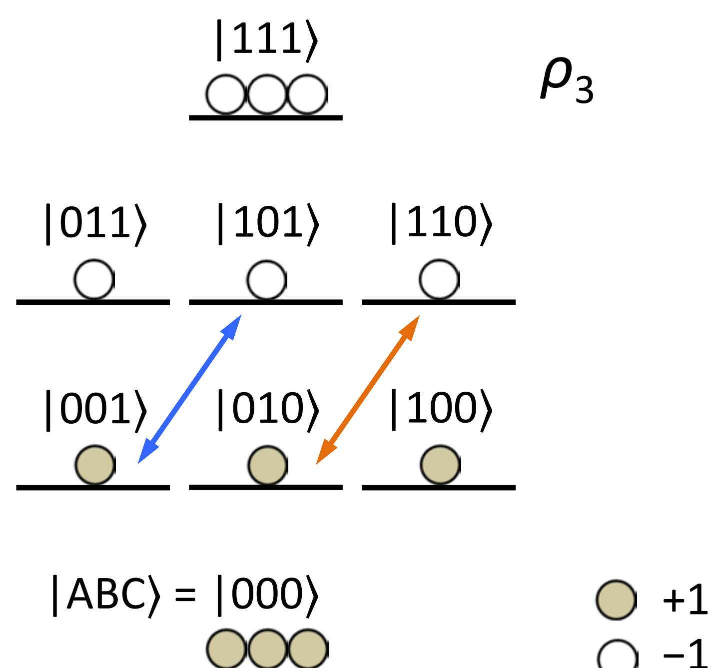
Logical labeling

Case study: *n* = 3

$$d(\rho_3) = \begin{pmatrix} 3 \\ 1 \\ 1 \\ -1 \\ 1 \\ -1 \\ -1 \\ -3 \end{pmatrix}$$

Unitary operator for LL_3

$$V = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$



Logical labeling

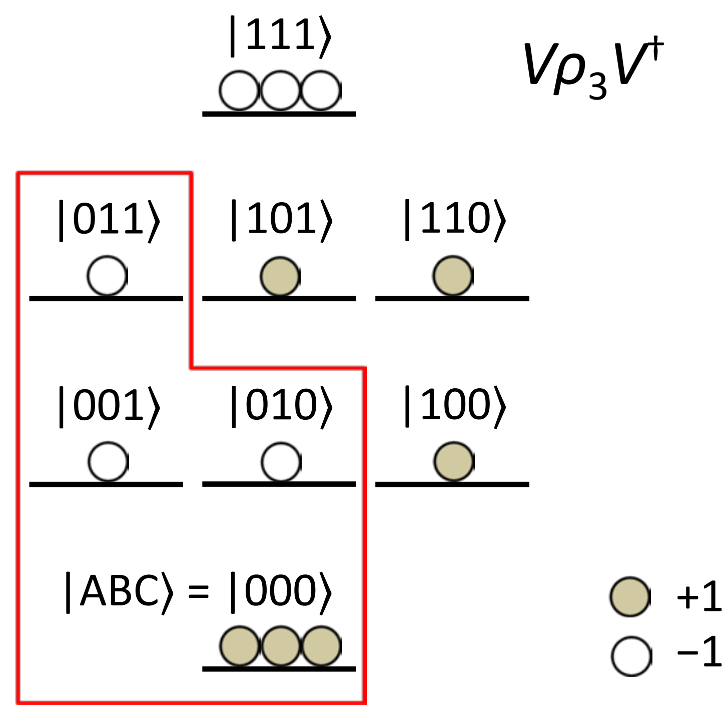
Case study: *n* = 3

$$d(\rho_3) = \begin{pmatrix} 3 \\ 1 \\ 1 \\ -1 \\ 1 \\ -1 \\ -1 \\ -3 \end{pmatrix} \Rightarrow d(V\rho_3 V^\dagger) = \begin{pmatrix} 3 \\ -1 \\ -1 \\ -1 \\ 1 \\ 1 \\ 1 \\ -3 \end{pmatrix} \approx \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

Sub-ensemble of BC labeled by A = 0 is pseudo-pure

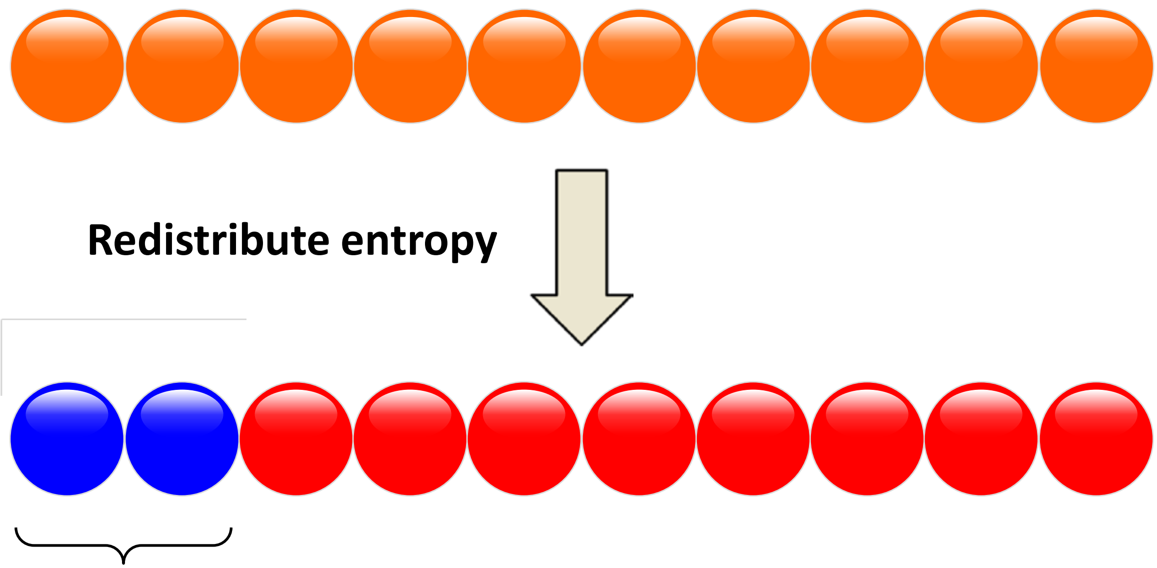
Unitary operator for LL_3

$$V = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

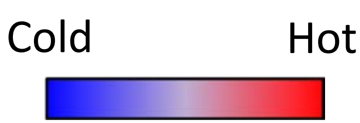


Algorithmic cooling

N-qubit array with polarization ϵ_0



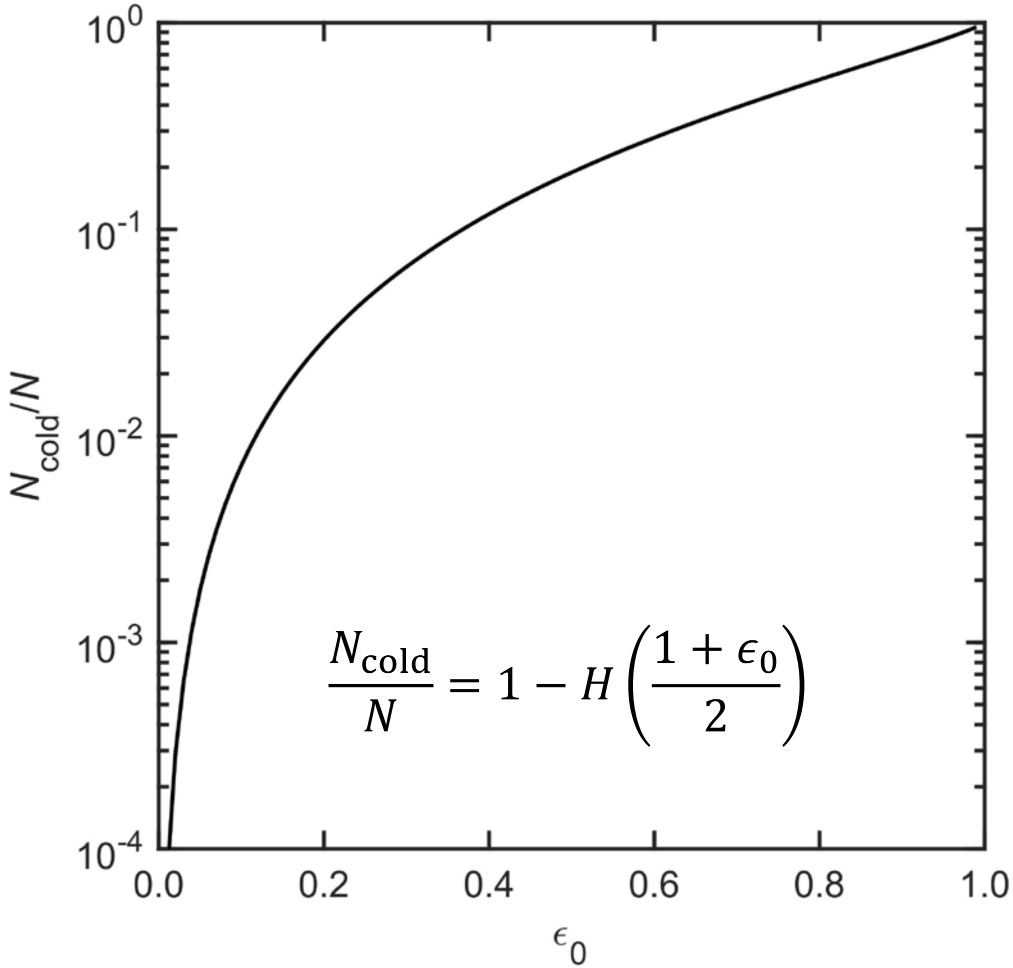
$$\frac{N_{\mathrm{cold}}}{N} = 1 - H\left(\frac{1+\epsilon_0}{2}\right)$$



Shannon entropy $H(p) = -p\log_2 p - (1-p)\log_2(1-p)$

Proc. 31st Annu. ACM Symp. Theory Compt. p.322 (1999) Schulman & Vazirani

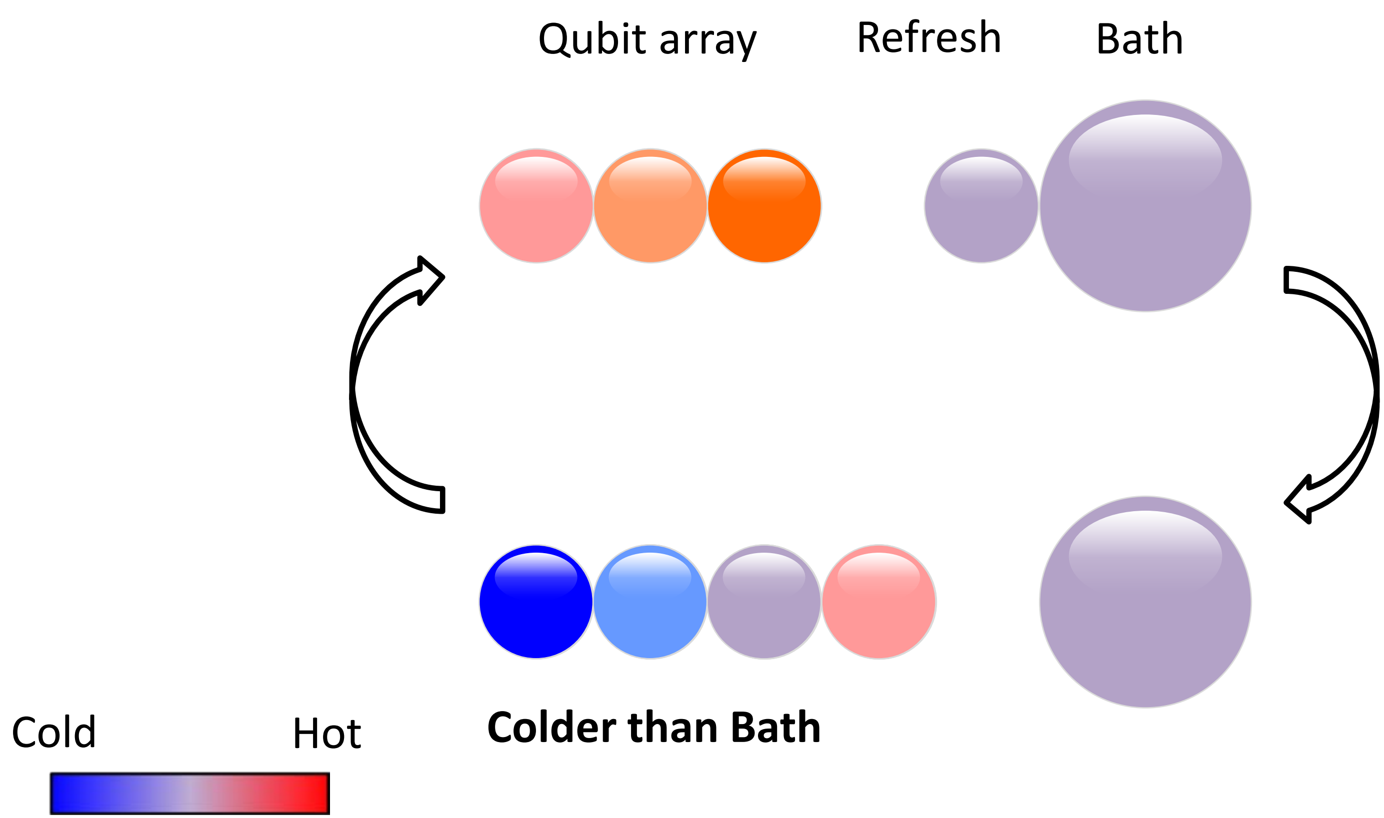
Algorithmic cooling



Proc. 31st Annu. ACM Symp. Theory Compt. p.322 (1999) Schulman & Vazirani

Heat bath algorithmic cooling

Iterative procedure to compress and pump out entropy from Qubits to Heat Bath

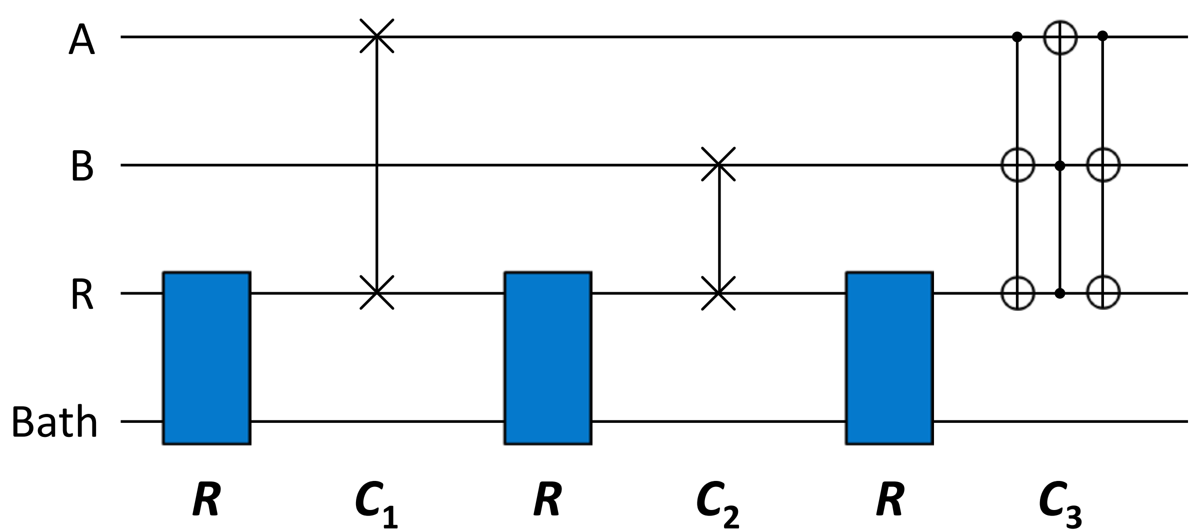


PNAS **99**, 3388 (2002) Boykin *at al.*

HBAC: Partner pairing algorithm

- ***R***: Thermalize R by contacting with Bath with polarization ϵ_b
- $\boldsymbol{C_1}$: Swap A and R ($|001\rangle \leftrightarrow |100\rangle$, $|011\rangle \leftrightarrow |110\rangle$)
- $\boldsymbol{C_2}$: Swap B and R ($|001\rangle \leftrightarrow |010\rangle$, $|101\rangle \leftrightarrow |110\rangle$)
- $\boldsymbol{C_3}$: Swap $|011\rangle$ and $|100\rangle$

Phys. Rev. Lett. **94**, 120501 (2005) Schulman *at al.*



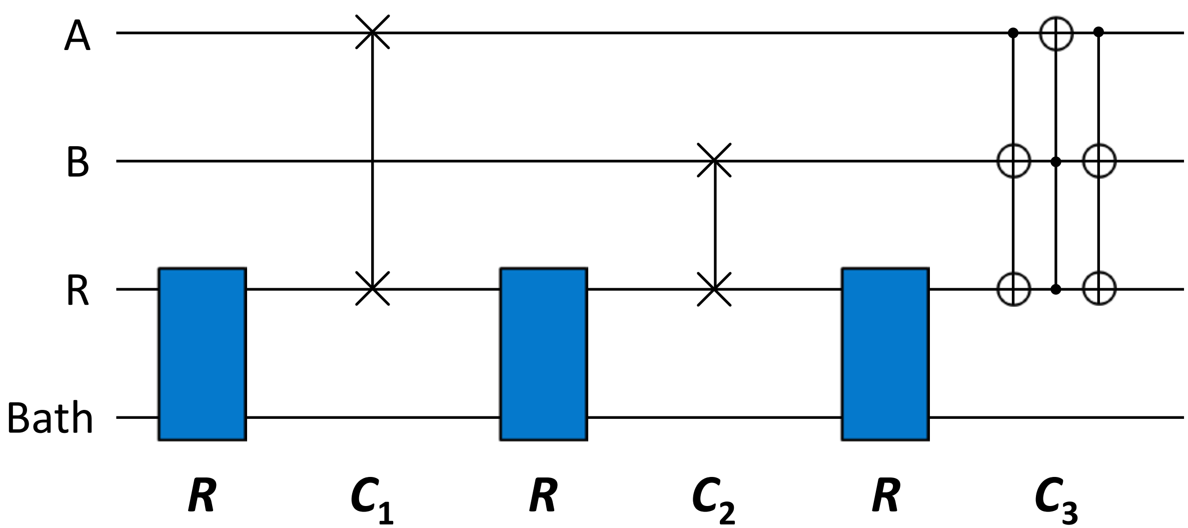
HBAC: 1st round

$$d(\rho_{\mathrm{I}}) = \frac{1}{8}\begin{pmatrix}1\\1\\1\\1\\1\\1\\1\\1\end{pmatrix} \xrightarrow{\boldsymbol{R}} d\left(\rho_{\mathrm{I}}^{R}\right) = \frac{1}{8}\begin{pmatrix}1+\epsilon_{\mathrm{b}}\\1-\epsilon_{\mathrm{b}}\\1+\epsilon_{\mathrm{b}}\\1-\epsilon_{\mathrm{b}}\\1+\epsilon_{\mathrm{b}}\\1-\epsilon_{\mathrm{b}}\\1+\epsilon_{\mathrm{b}}\\1-\epsilon_{\mathrm{b}}\end{pmatrix} \xrightarrow{\boldsymbol{C_1}} d\left(C_1\rho_{\mathrm{I}}^{R}C_1^{\dagger}\right) = \frac{1}{8}\begin{pmatrix}1+\epsilon_{\mathrm{b}}\\1+\epsilon_{\mathrm{b}}\\1+\epsilon_{\mathrm{b}}\\1+\epsilon_{\mathrm{b}}\\1-\epsilon_{\mathrm{b}}\\1-\epsilon_{\mathrm{b}}\\1-\epsilon_{\mathrm{b}}\\1-\epsilon_{\mathrm{b}}\end{pmatrix}$$

p(A): $0 \rightarrow \epsilon_{\mathrm{b}}$

p(B): $0 \rightarrow 0$

p(R): $0 \rightarrow 0$



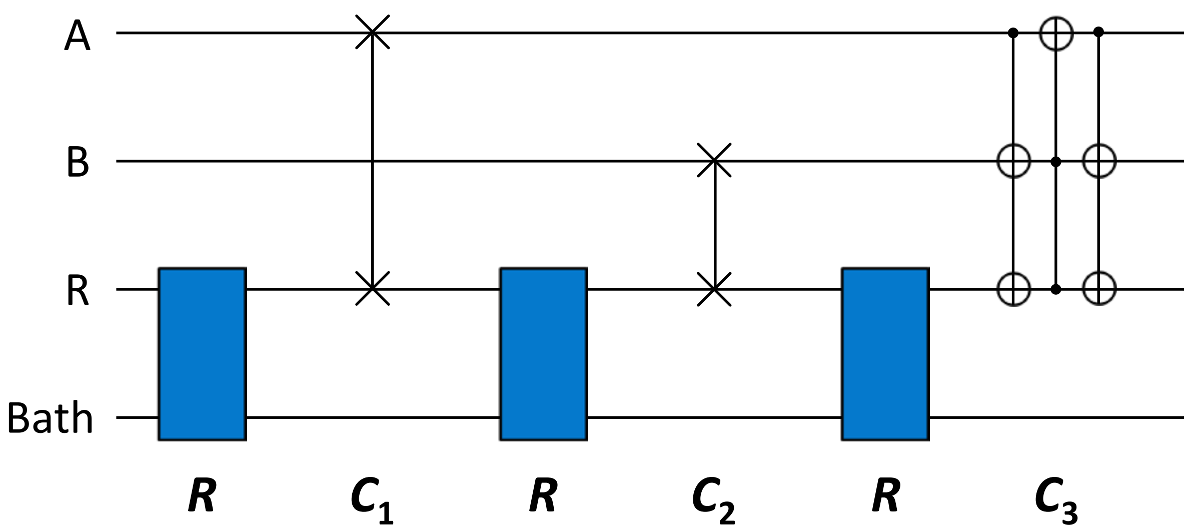
HBAC: 1st round

$$\xrightarrow{\boldsymbol{R}} d\left((C_1\rho_{\mathrm{I}}^R C_1^\dagger)^R\right) = \frac{1}{8}\begin{pmatrix}(1+\epsilon_{\mathrm{b}})^2\\ 1-\epsilon_{\mathrm{b}}^2\\ (1+\epsilon_{\mathrm{b}})^2\\ 1-\epsilon_{\mathrm{b}}^2\\ 1-\epsilon_{\mathrm{b}}^2\\ (1-\epsilon_{\mathrm{b}})^2\\ 1-\epsilon_{\mathrm{b}}^2\\ (1-\epsilon_{\mathrm{b}})^2\end{pmatrix} \xrightarrow{\boldsymbol{C_2}} d\left(C_2(C_1\rho_{\mathrm{I}}^R C_1^\dagger)^R C_2^\dagger\right) = \frac{1}{8}\begin{pmatrix}(1+\epsilon_{\mathrm{b}})^2\\ (1+\epsilon_{\mathrm{b}})^2\\ 1-\epsilon_{\mathrm{b}}^2\\ 1-\epsilon_{\mathrm{b}}^2\\ 1-\epsilon_{\mathrm{b}}^2\\ 1-\epsilon_{\mathrm{b}}^2\\ (1-\epsilon_{\mathrm{b}})^2\\ (1-\epsilon_{\mathrm{b}})^2\end{pmatrix}$$

p(A): $\epsilon_{\mathrm{b}} \rightarrow \epsilon_{\mathrm{b}}$

p(B): $0 \rightarrow \epsilon_{\mathrm{b}}$

p(R): $0 \rightarrow 0$



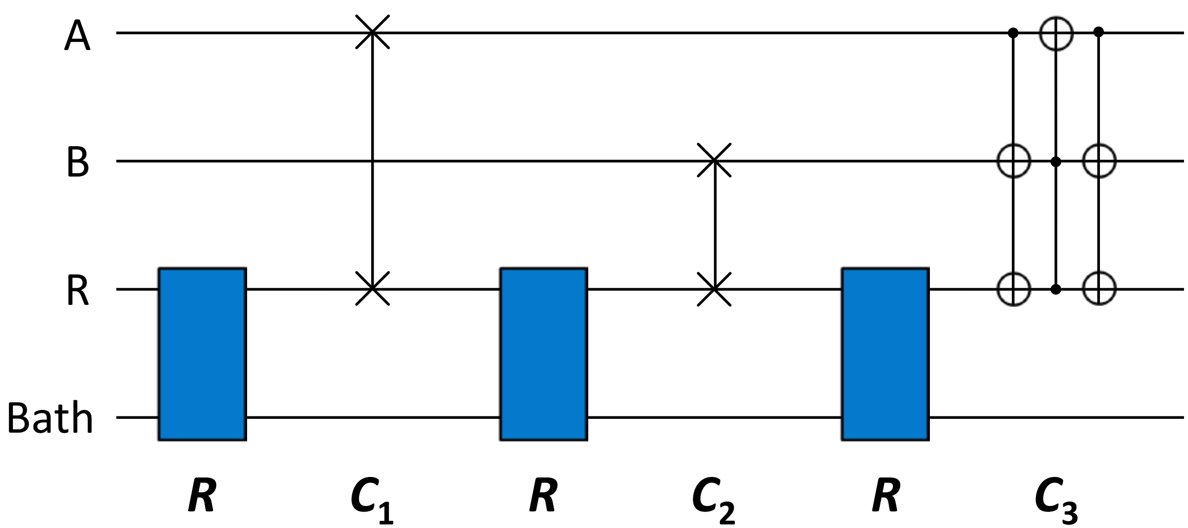
HBAC: 1st round

$$\xrightarrow{R} \quad \xrightarrow{C_3} d\left(C_3(C_2(C_1\rho_{\mathrm{I}}^{R}C_1^{\dagger})^{R}C_2^{\dagger})^{R}C_3^{\dagger}\right) = \frac{1}{8}\begin{pmatrix}(1+\epsilon_{\mathrm{b}})^3\\(1+\epsilon_{\mathrm{b}})^2(1-\epsilon_{\mathrm{b}})\\(1+\epsilon_{\mathrm{b}})^2(1-\epsilon_{\mathrm{b}})\\(1+\epsilon_{\mathrm{b}})^2(1-\epsilon_{\mathrm{b}})\\(1+\epsilon_{\mathrm{b}})(1-\epsilon_{\mathrm{b}})^2\\(1+\epsilon_{\mathrm{b}})(1-\epsilon_{\mathrm{b}})^2\\(1+\epsilon_{\mathrm{b}})(1-\epsilon_{\mathrm{b}})^2\\(1-\epsilon_{\mathrm{b}})^3\end{pmatrix}$$

$p(\mathrm{A})$: $\epsilon_{\mathrm{b}} \rightarrow 1.5\epsilon_{\mathrm{b}} - 0.5\epsilon_{\mathrm{b}}^3$

$p(\mathrm{B})$: $\epsilon_{\mathrm{b}} \rightarrow 0.5\epsilon_{\mathrm{b}} + 0.5\epsilon_{\mathrm{b}}^3$

$p(\mathrm{R})$: $0 \rightarrow 0.5\epsilon_{\mathrm{b}} + 0.5\epsilon_{\mathrm{b}}^3$



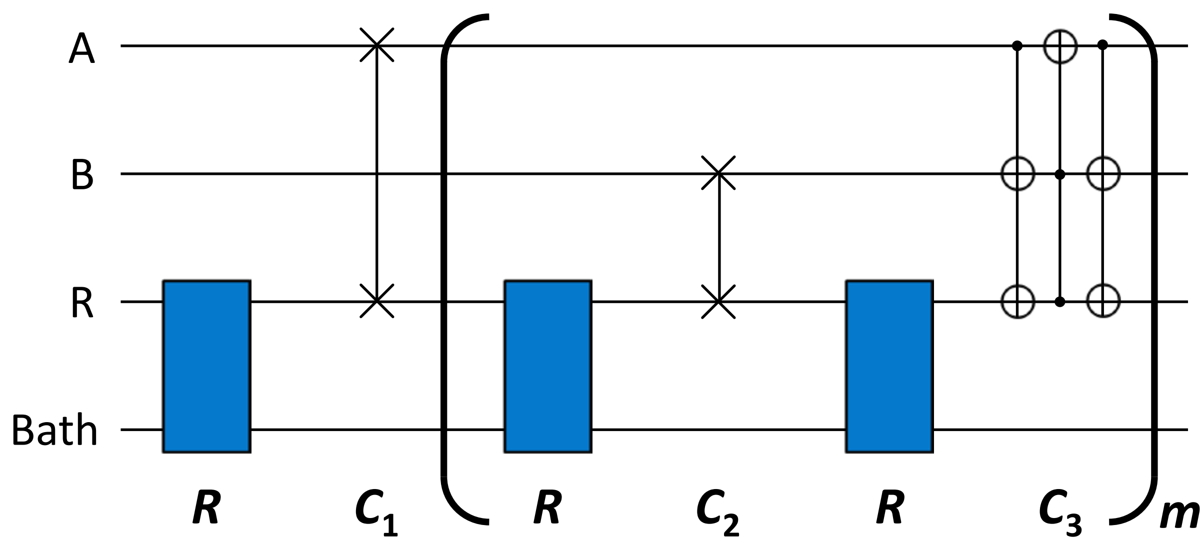
HBAC: Multiple rounds

$$\xrightarrow{\boldsymbol{R}}$$

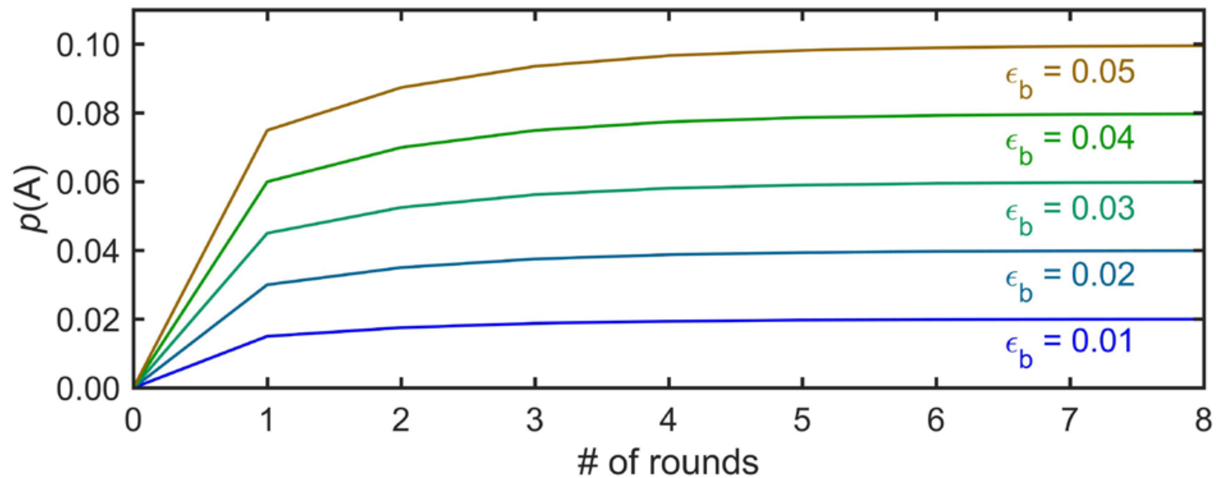
$p(\mathrm{A})$: $1.5\epsilon_b - 0.5\epsilon_b^3 \rightarrow \ldots$

$p(\mathrm{B})$: $0.5\epsilon_b + 0.5\epsilon_b^3 \rightarrow \ldots$

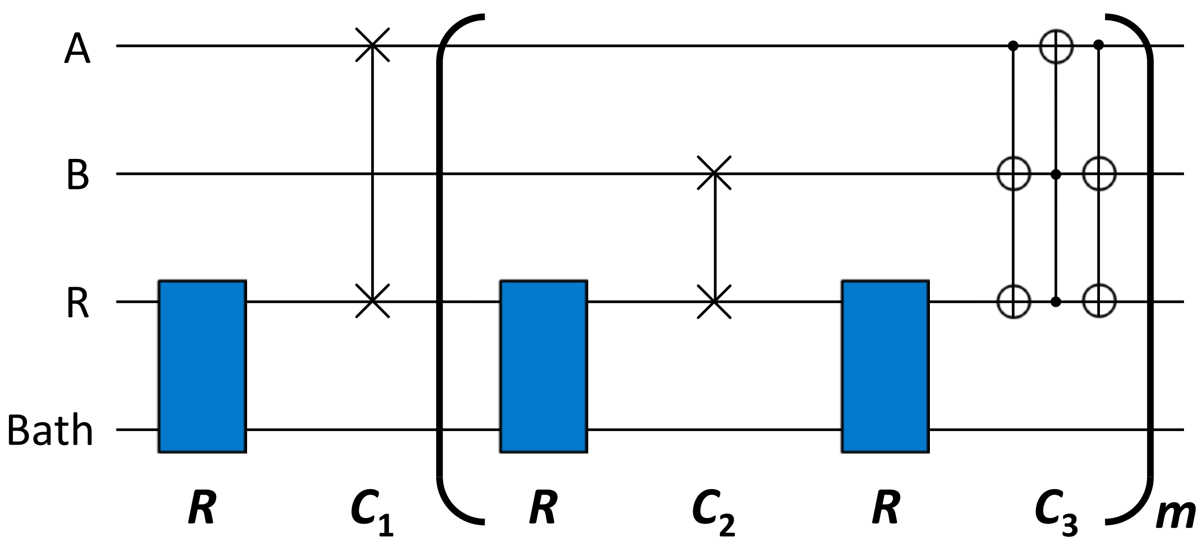
$p(\mathrm{R})$: $0.5\epsilon_b + 0.5\epsilon_b^3 \rightarrow \epsilon_b$



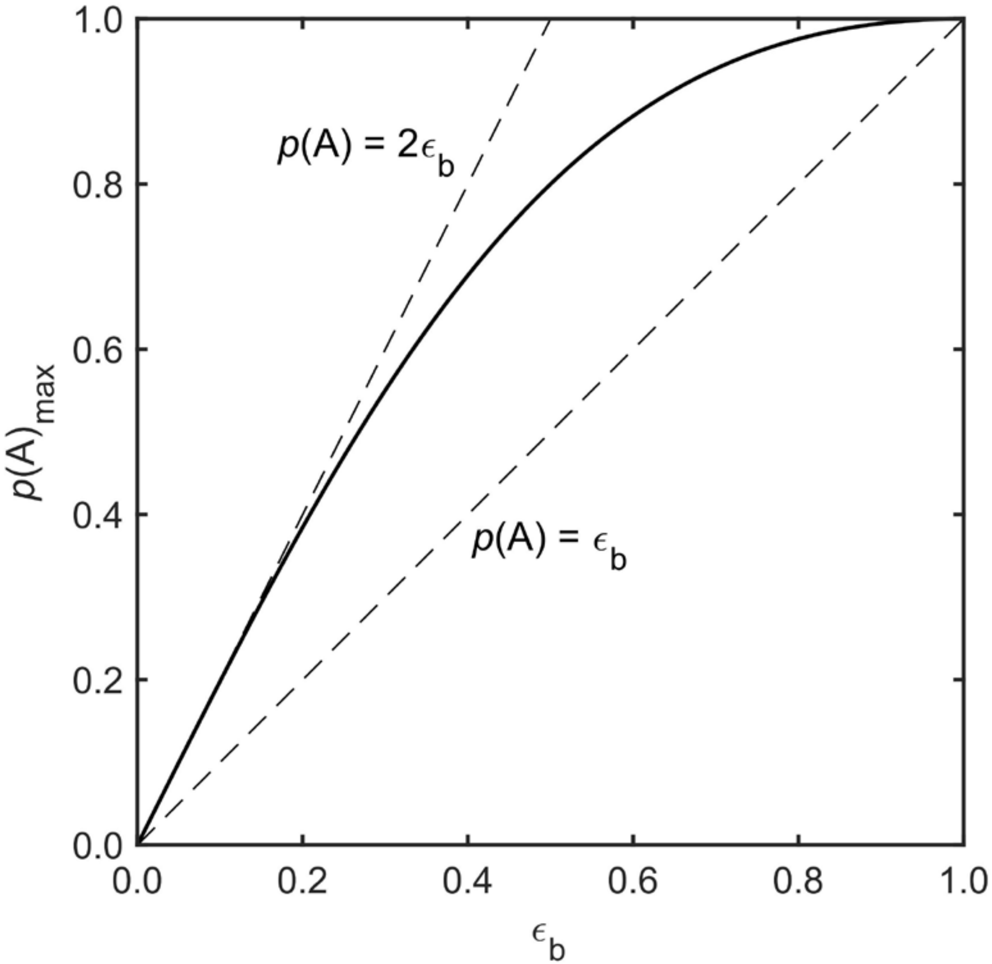
HBAC: Multiple rounds



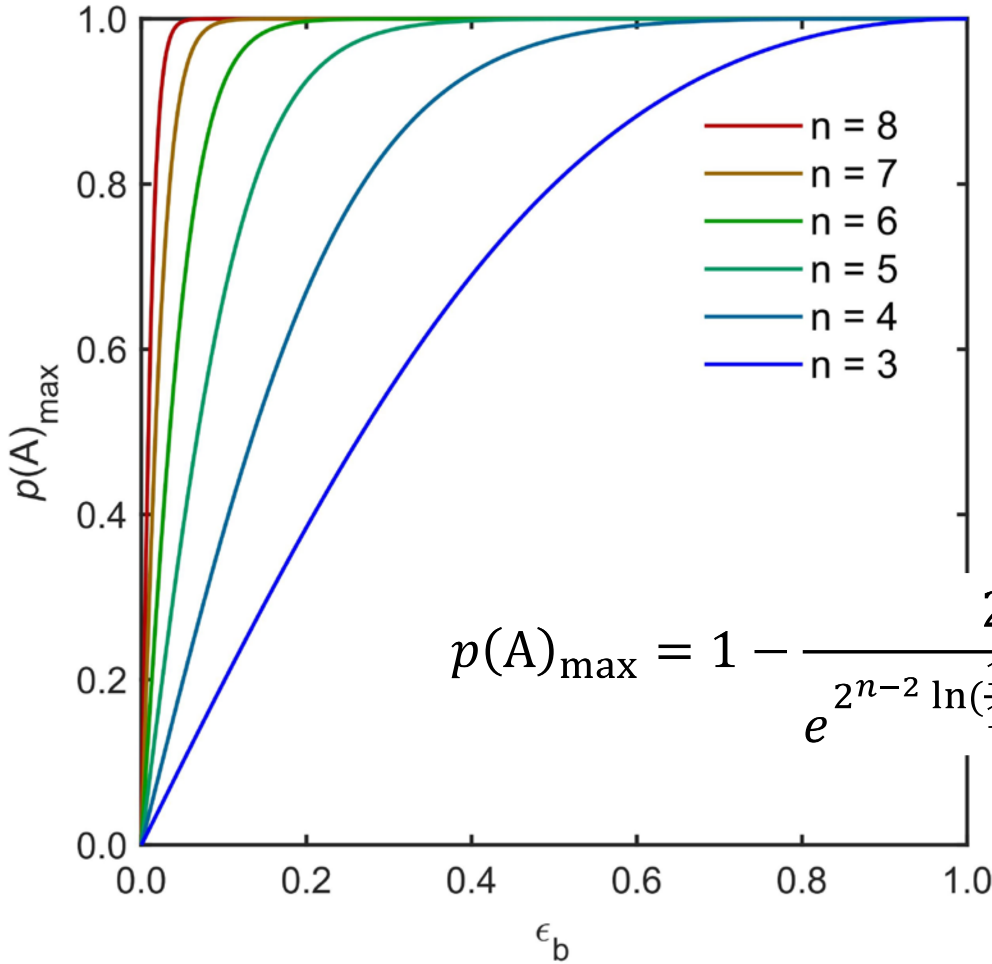
$p(\mathrm{A}) \rightarrow 2\epsilon_{\mathrm{b}}$ (?)



HBAC: Achievable polarization



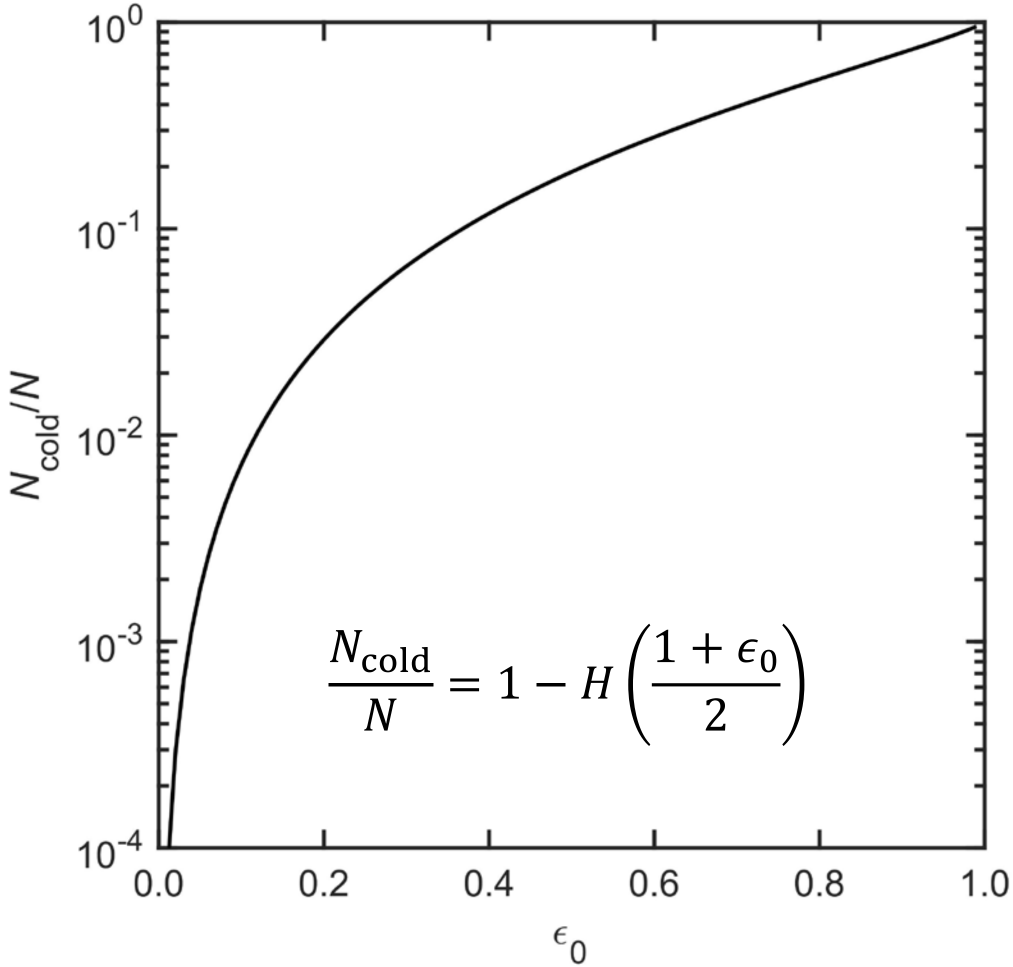
HBAC: Achievable polarization



$$p(\mathrm{A})_{\max} = 1 - \frac{2}{e^{2^{n-2}\ln\left(\frac{1+\epsilon_b}{1-\epsilon_b}\right)} + 1}$$

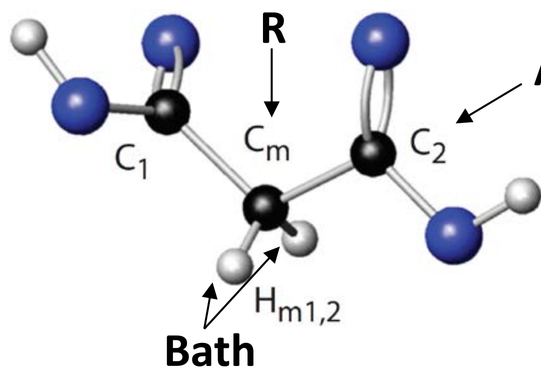
Phys. Rev. Lett. **116**, 170501 (2016) Rodriguez-Briones & Laflamme

Algorithmic cooling

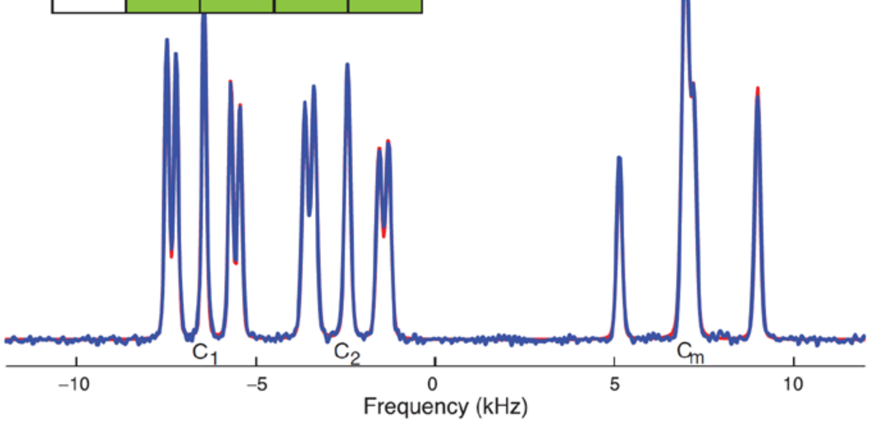


Proc. 31st Annu. ACM Symp. Theory Compt. p.322 (1999) Schulman & Vazirani

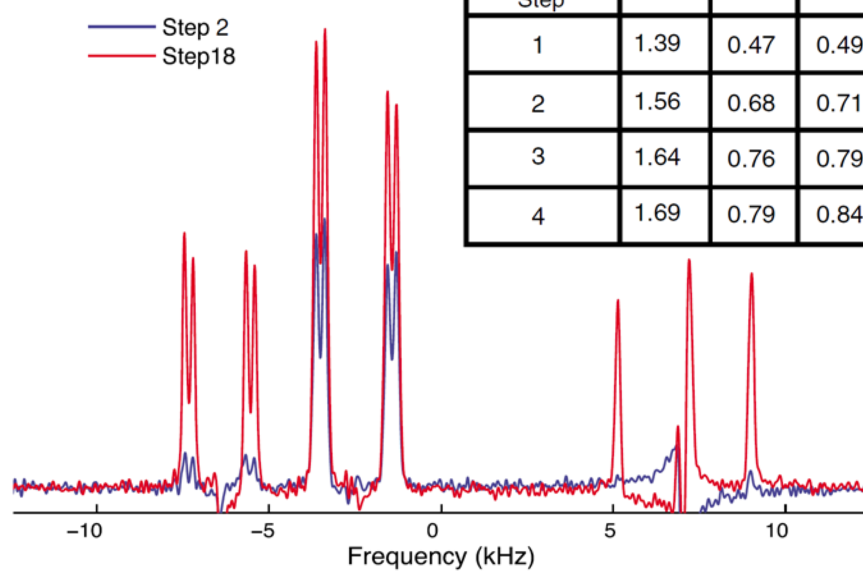
HBAC: Experiments



kHz	C_1	C_2	C_m	H_{m1}
C_1	-6.442	-0.005	0.05	
C_2	0.131	-2.442	0.05	
C_m	-0.918	1.013	7.028	
H_{m1}	-2.9	0.2	-11.4	
H_{m2}	-0.3	1.4	11.0	5.6



Compression Step	C_2	C_1	C_m
1	1.39	0.47	0.49
2	1.56	0.68	0.71
3	1.64	0.76	0.79
4	1.69	0.79	0.84



Nature **438**, 470 (2005) Baugh *et al.*

Phys. Rev. Lett. **100**, 140501 (2008) Ryan *et al.*

Scalable approaches

- **Large DNP on ensemble**
  - Hard...
- **HBAC on ensemble**
  - Harder...?
- **Measure-and-flip on individual spins**
  - Hardest...??

Scalable approaches

- **Large DNP on ensemble**
  - Hard...
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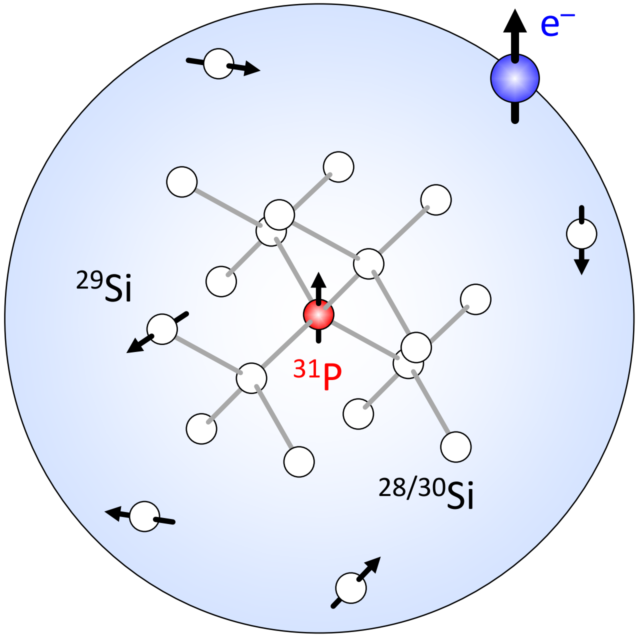
- **Measure-and-flip on individual spins**
  - Hardest...??

In a few rare systems (Si:P, NV...), we can.

The technique used is closely related to DNP.

Phosphorus donor in silicon

III (13)	IV (14)	V (15)
B	C	N
Al	**Si**	**P**
Ga	Ge	As

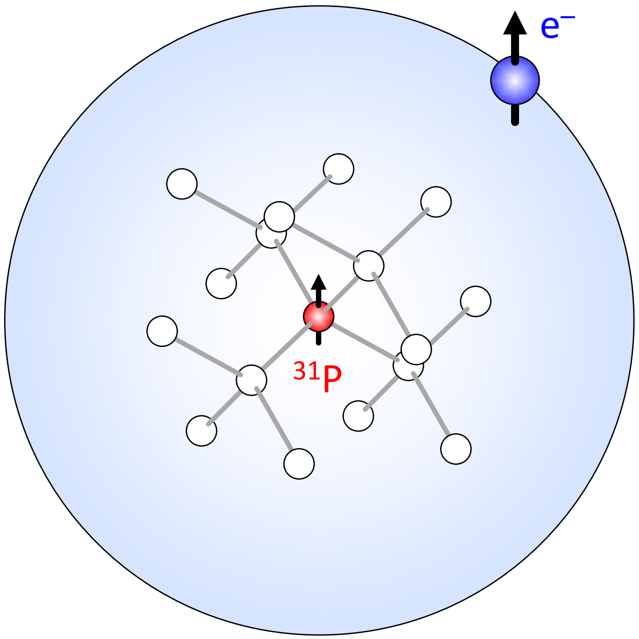


^{28}Si : ^{29}Si (I = ½) : ^{30}Si = 92.2% : 4.7% : 3.1%

^{31}P (I = ½) = 100%

Phosphorus donor in silicon

III (13)	IV (14)	V (15)
B	C	N
Al	**Si**	**P**
Ga	Ge	As



Isotopically purified ^{28}Si (99.995%)

^{31}P (I = ½) = 100%

Energy levels of Si:P

Hamiltonian

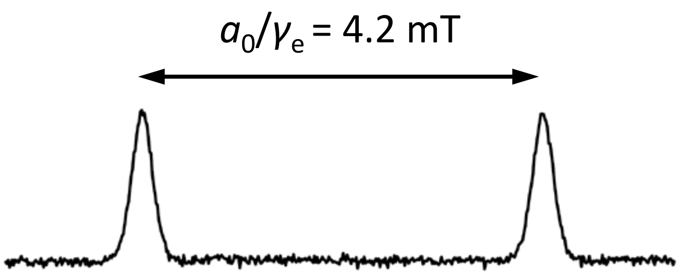
$$H_0 = \gamma_e B_0 S_z - \gamma_P B_0 I_z + a_0 S_z I_z$$

B_0 ~ 350 mT (X-band)

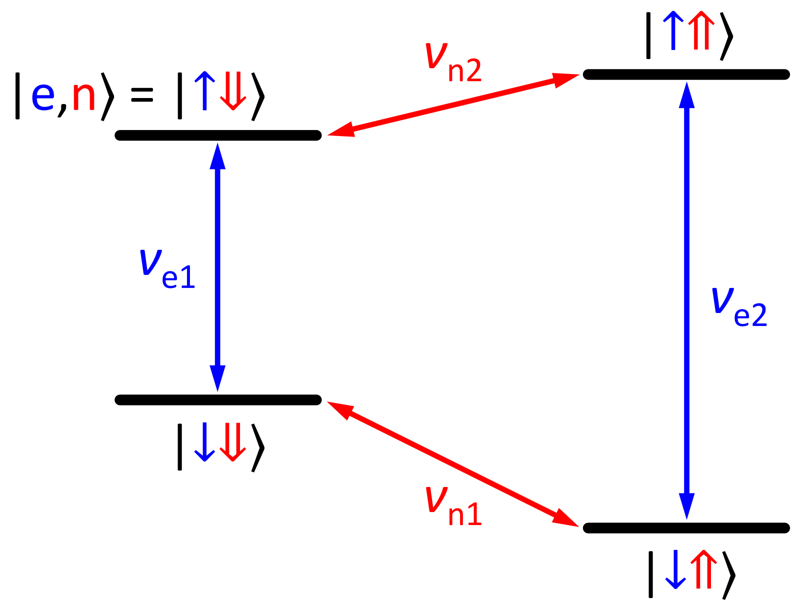
γ_e = 27.97 GHz/T

γ_P = 17.23 MHz/T

a_0 = 117.53 MHz



Field-sweep ESR spectrum



$\nu_{e1} = \gamma_e B_0 - a_0/2$ $\nu_{e2} = \gamma_e B_0 + a_0/2$

$\nu_{n1} = a_0/2 + \gamma_P B_0$ $\nu_{n2} = a_0/2 - \gamma_P B_0$

Method of Polarizing Nuclei in Paramagnetic Substances

G. FEHER
Bell Telephone Laboratories, Murray Hill, New Jersey
(Received May 31, 1956)

OVERHAUSER[1] has shown that a saturation of the electron spin resonance leads to a large enhancement of the nuclear polarization. A necessary condition for this enhancement is that the nuclei relax via the electrons whose resonance is being saturated.

The scheme proposed in this paper, applicable to substances which show a resolved hyperfine structure, places no requirements on the detailed relaxation mechanism of either the electron or the nucleus. It requires, however, that one sweep through a certain fraction of the external magnetic field in a time short compared to either relaxation time.

(©R.A. Icaacson)

Phys. Rev. **103**, 500 (1956) Feher

Polarization of Phosphorus Nuclei in Silicon

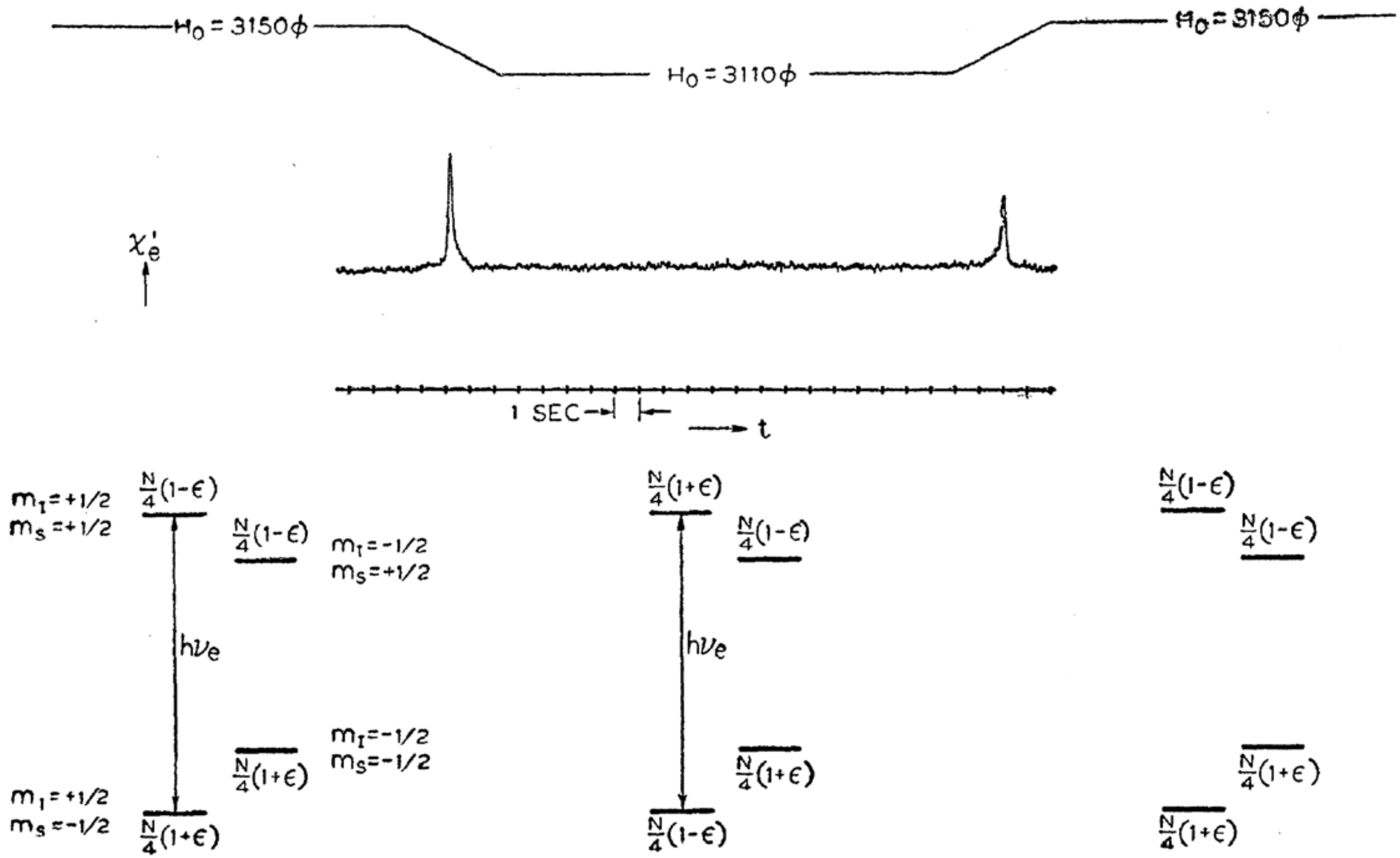
G. FEHER AND E. A. GERE
Bell Telephone Laboratories, Murray Hill, New Jersey
(Received May 31, 1956)

IN the preceding Letter a scheme for polarizing nuclei was described. This Letter deals with the experimental verification of the scheme.

Phys. Rev. **103**, 501 (1956) Feher & Gere

Polarization of Phosphorus Nuclei in Silicon

G. Feher and E. A. Gere
Bell Telephone Laboratories, Murray Hill, New Jersey
(Received May 31, 1956)



(π-pulse on *e*-spin)

Phys. Rev. **103**, 501 (1956) Feher & Gere

Polarization of Phosphorus Nuclei in Silicon

G. Feher and E. A. Gere

Bell Telephone Laboratories, Murray Hill, New Jersey

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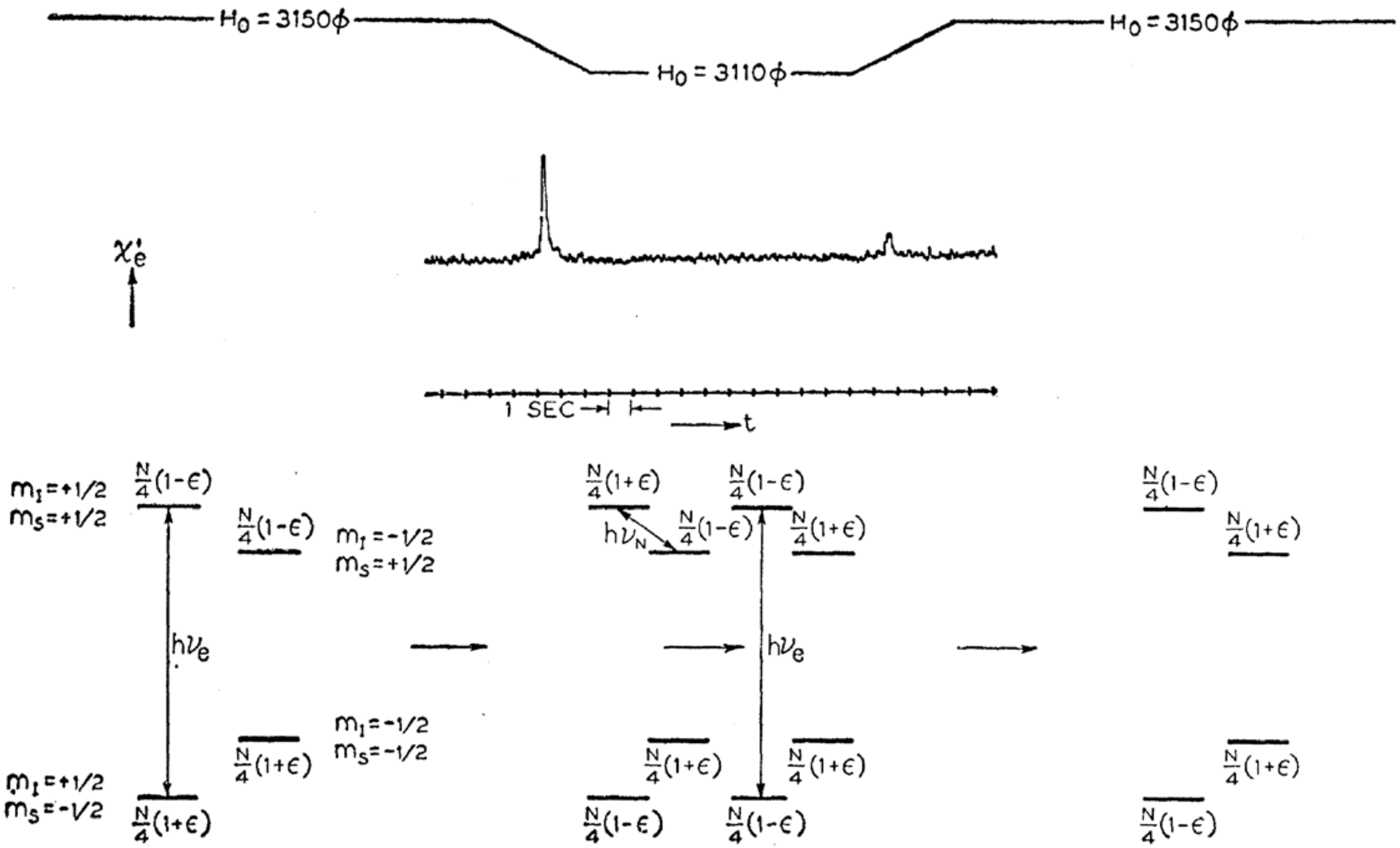
Electron Nuclear DOuble Resonance



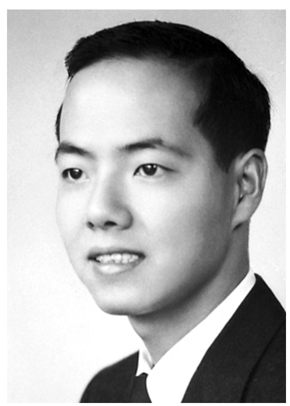
(*π*-pulse on *e*-spin) **(*π*-pulse on *n*-spin)**

Phys. Rev. **103**, 501 (1956) Feher & Gere

ENDOR & parity non-conservation

[…] In the fall of 1956, I gave a colloquium at Columbia University on the nuclear polarization scheme. After the colloquium, C. S. Wu and T. D. Lee excitedly tried to persuade me to measure the asymmetry of β-decay in a polarized sample of donor nuclei in silicon. T. D. Lee and C. N. Yang had circulated a preprint of an article in which they suggested that one of the conservation laws of physics, parity, did not hold in the case of weak interactions. [...] I listened politely with limited interest and promised them I would get to it as soon as I finished the ENDOR experiments [...]

C. S. Wu
(©AIP Emilio Segre Visual Archives)



T. D. Lee
(©Nobel Foundation)

C. N. Yang
(©Nobel Foundation)

Annu. Rev. Biophys. Biomol. Struct. **31**, 1 (2002) Feher

ENDOR & parity non-conservation

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After finishing these at the end of 1956, I took an extended skiing vacation in the West. On the way back I stopped off at the University of Pittsburgh where I gave a colloquium [...] At the conclusion, I mentioned that I would like to test Lee & Yang's hypothesis of parity nonconservation. [...] it felt as if the temperature of the room had dropped by 10 degrees. Finally, G. C. Wick said, "But don't you know that parity nonconservation has already been proven by several groups?". Of course, I did not know; I had been skiing for a month.

Annu. Rev. Biophys. Biomol. Struct. **31**, 1 (2002) Feher

Quantum Computation

David P. DiVincenzo

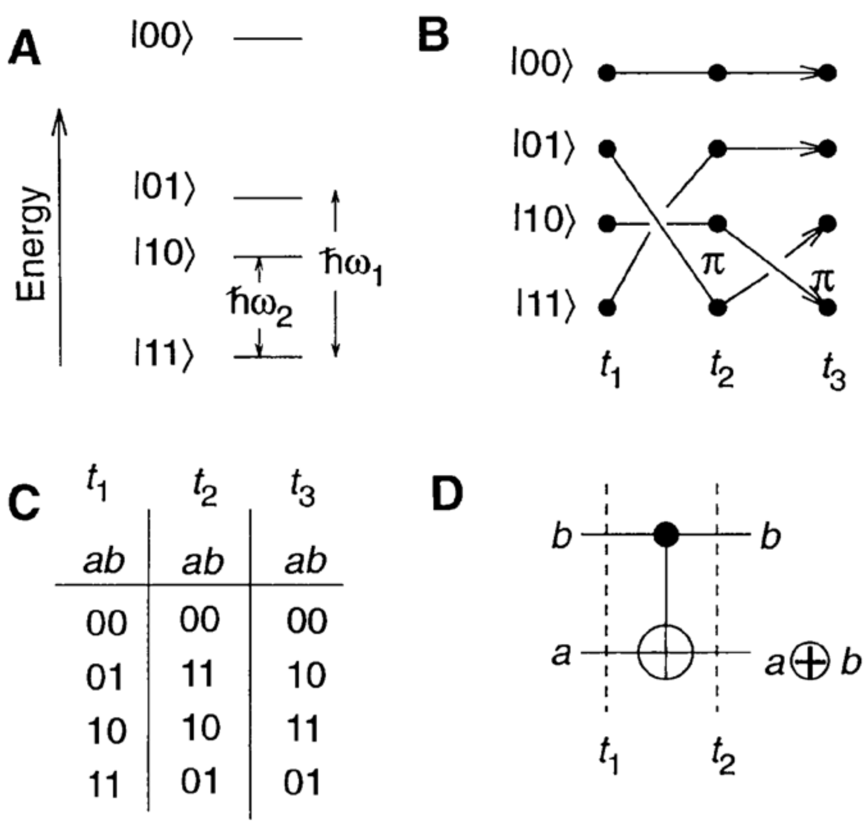


Fig. 2. The action of the two-qubit XOR gate.

The XOR protocol is very closely related to procedures invented long ago in the field of resonance spectroscopies (*13*). In 1956, Feher introduced a procedure for polarization transfer in electron-nucleus double resonance (ENDOR), which contains the XOR protocol just discussed.

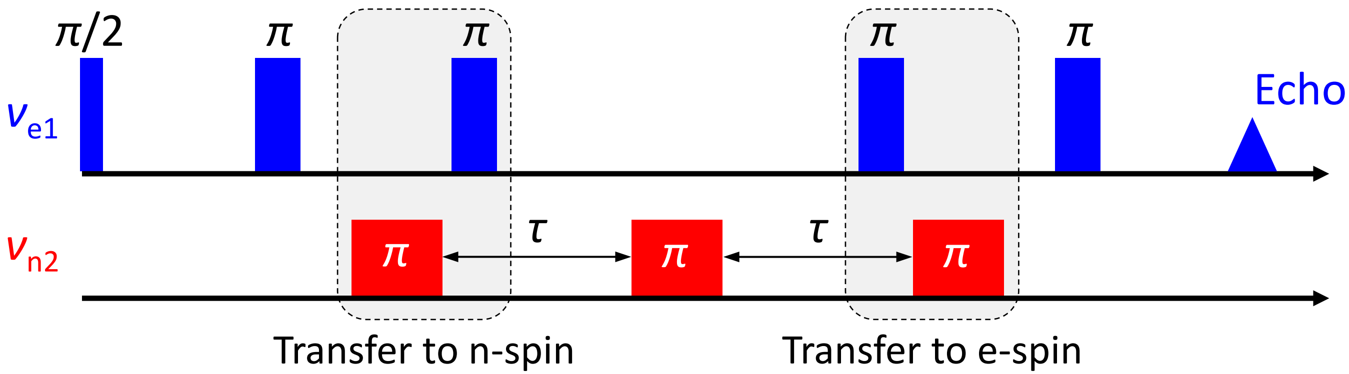
for many purposes in physics, chemistry, and biology, it is highly desirable to move the spin state of an electron onto a nearby nucleus. The fact that this procedure also performs an interesting logical function, XOR, was not previously noted by ENDOR spectroscopists.

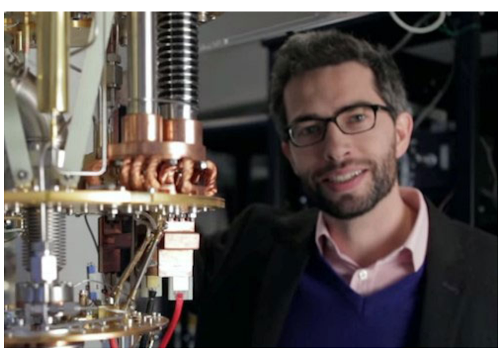
Science **270**, 255 (1995) DiVincenzo

LETTERS

Solid-state quantum memory using the ^{31}P nuclear spin

John J. L. Morton[1,2], Alexei M. Tyryshkin[3], Richard M. Brown[1], Shyam Shankar[3], Brendon W. Lovett[1], Arzhang Ardavan[2], Thomas Schenkel[4], Eugene E. Haller[4,5], Joel W. Ager[4] & S. A. Lyon[3]





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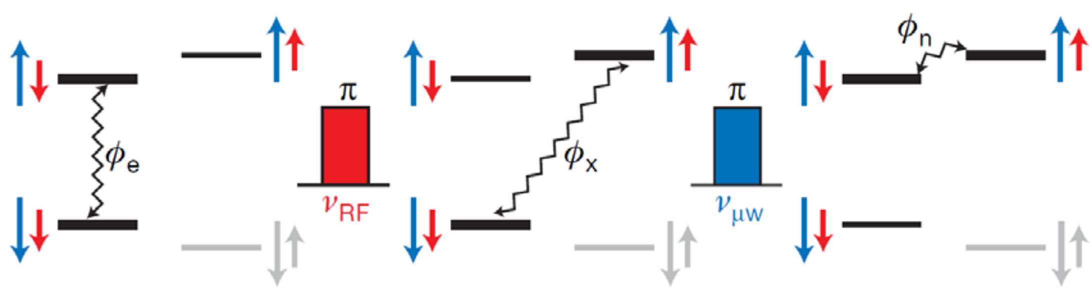


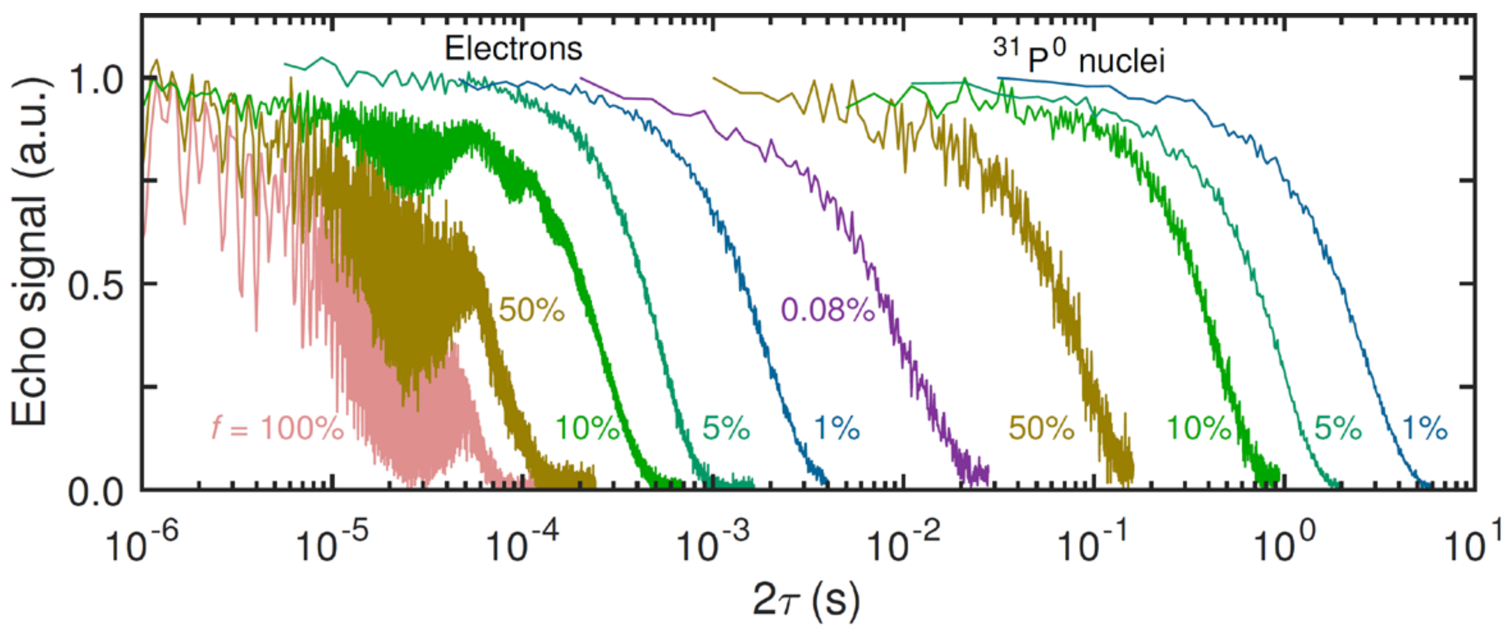
Nature **455**, 1085 (2008) Morton *et al.*

Electron spin coherence of phosphorus donors in silicon: Effect of environmental nuclei

Eisuke Abe,[1,2,*] Alexei M. Tyryshkin,[3] Shinichi Tojo,[2] John J. L. Morton,[1,4] Wayne M. Witzel,[5] Akira Fujimoto,[2] Joel W. Ager,[6] Eugene E. Haller,[6,7] Junichi Isoya,[8] Stephen A. Lyon,[3] Mike L. W. Thewalt,[9] and Kohei M. Itoh[2]

Nuclear spin decoherence of neutral ^{31}P donors in silicon: Effect of environmental ^{29}Si nuclei

Evan S. Petersen,[1] A. M. Tyryshkin,[1] J. J. L. Morton,[2] E. Abe,[3] S. Tojo,[3] K. M. Itoh,[3] M. L. W. Thewalt,[4] and S. A. Lyon[1]



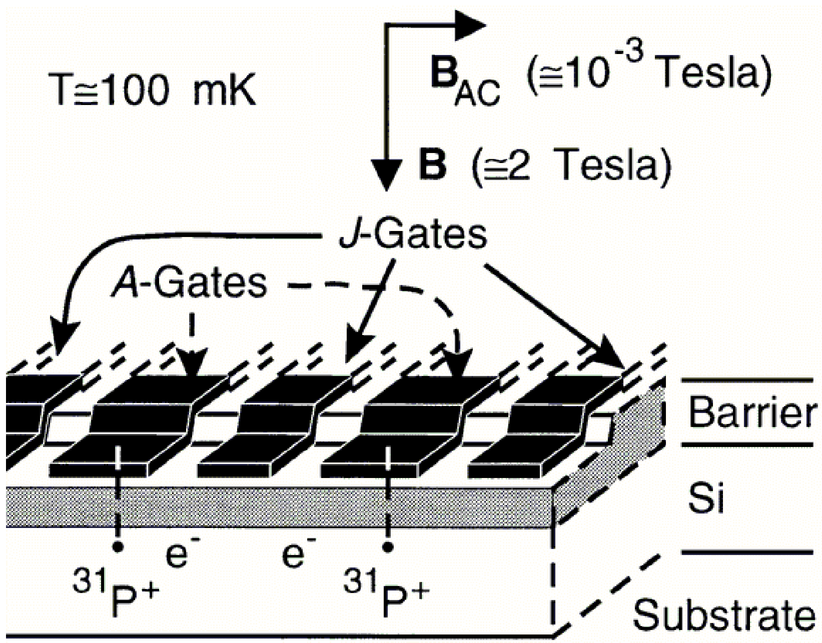
Phys. Rev. B **82**, 121201 (2010) Abe *et al.*

Phys. Rev. B **93**, 161202 (2016) Petersen *et al.*

A silicon-based nuclear spin quantum computer

B. E. Kane

Semiconductor Nanofabrication Facility, School of Physics, University of New South Wales, Sydney 2052, Australia



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Nature **393**, 133 (1998) Kane

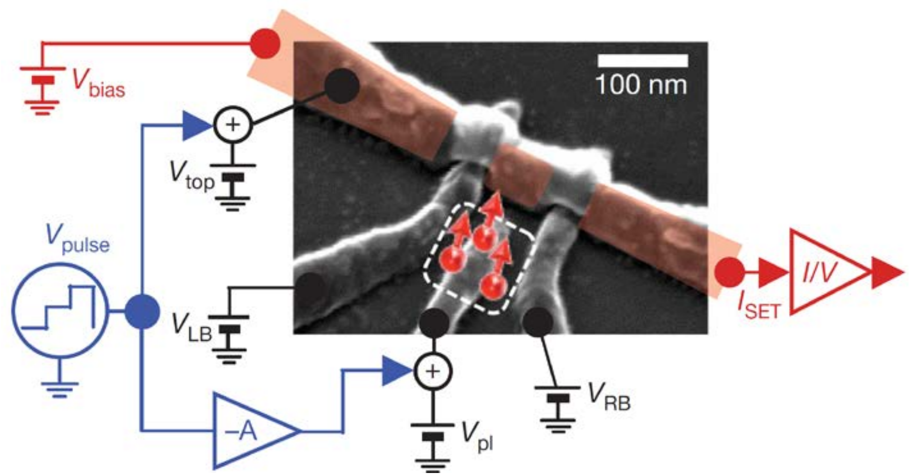
Cf. Nature **393**, 143 (1998) Chuang *et al. “Experimental realization of a quantum algorithm”*

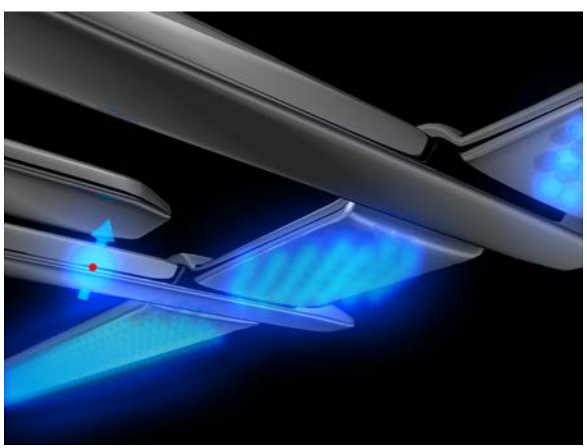
LETTER

doi:10.1038/nature09392

Single-shot readout of an electron spin in silicon

Andrea Morello[1], Jarryd J. Pla[1], Floris A. Zwanenburg[1], Kok W. Chan[1], Kuan Y. Tan[1], Hans Huebl[1]†, Mikko Möttönen[1,3,4], Christopher D. Nugroho[1]†, Changyi Yang[2], Jessica A. van Donkelaar[2], Andrew D. C. Alves[2], David N. Jamieson[2], Christopher C. Escott[1], Lloyd C. L. Hollenberg[2], Robert G. Clark[1]† & Andrew S. Dzurak[1]





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Nature **497**, 687 (2010) Morello *et al.*

LETTER

doi:10.1038/nature09392

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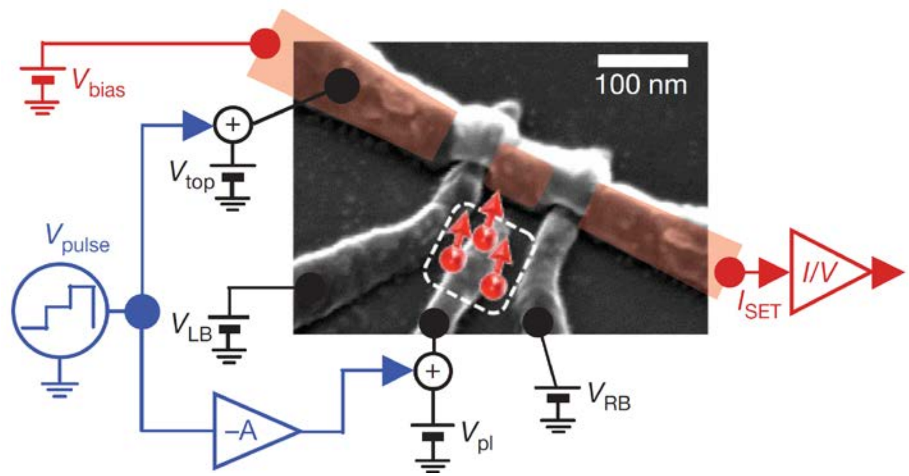
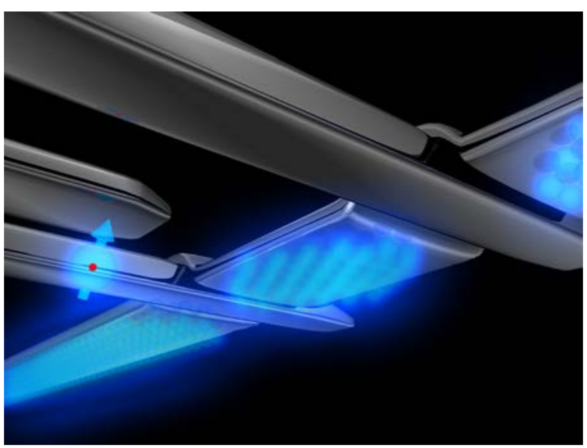
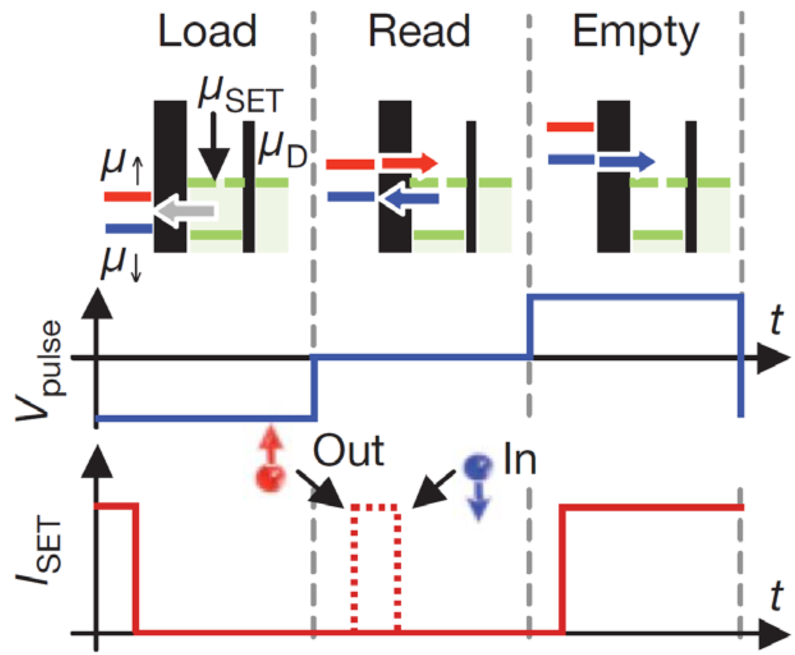






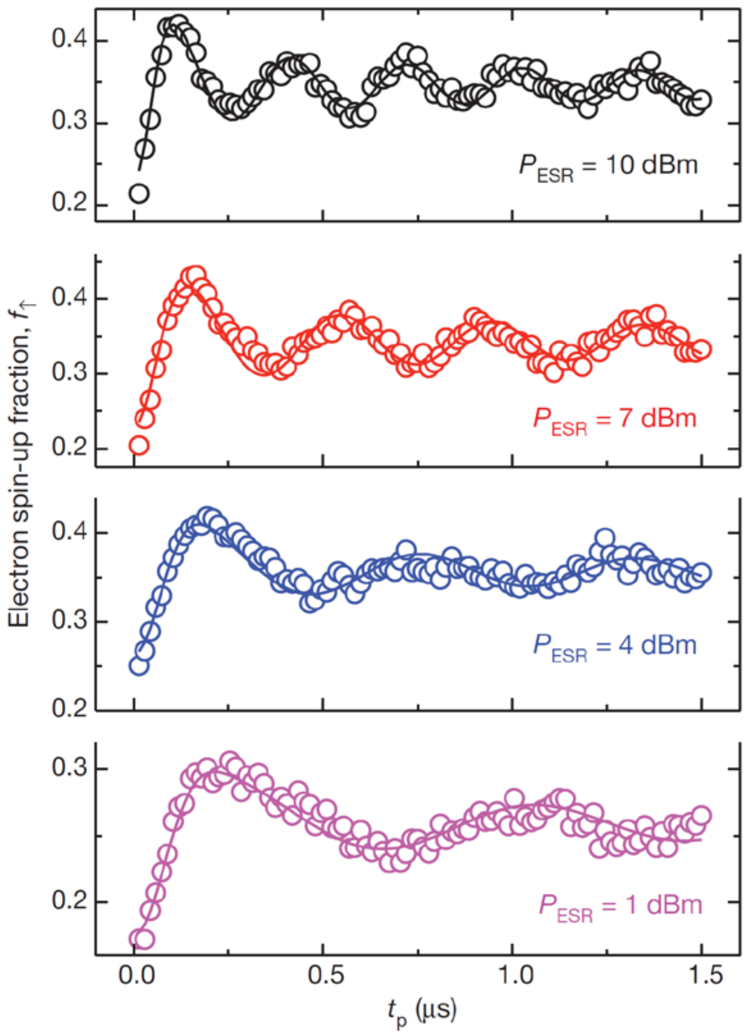
Nature **497**, 687 (2010) Morello *et al.*

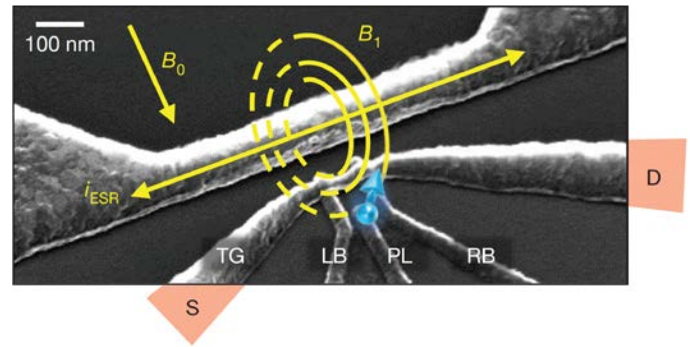
LETTER

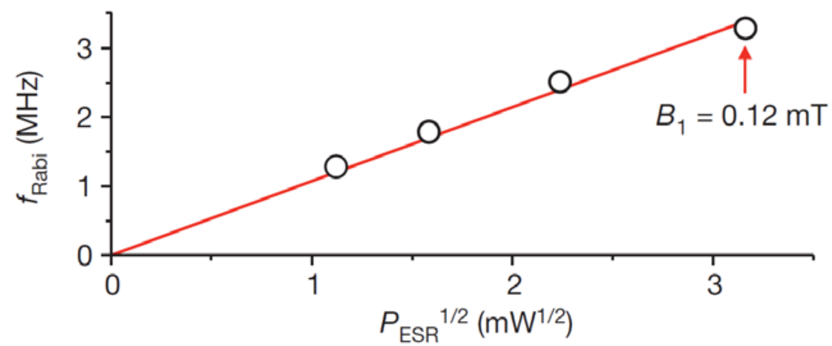
doi:10.1038/nature11449

A single-atom electron spin qubit in silicon

Jarryd J. Pla[1], Kuan Y. Tan[1]†, Juan P. Dehollain[1], Wee H. Lim[1], John J. L. Morton[2]†, David N. Jamieson[3], Andrew S. Dzurak[1] & Andrea Morello[1]







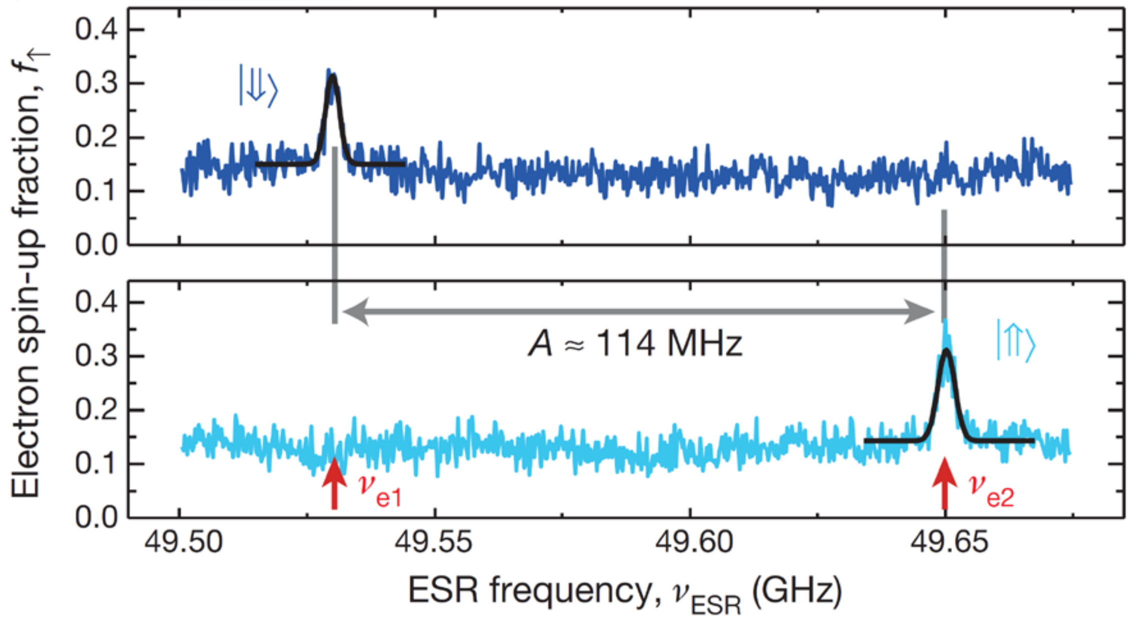
Nature **489**, 541 (2012) Pla *et al.*

LETTER

doi:10.1038/nature12011

High-fidelity readout and control of a nuclear spin qubit in silicon

Jarryd J. Pla[1], Kuan Y. Tan[1]†, Juan P. Dehollain[1], Wee H. Lim[1]†, John J. L. Morton[2], Floris A. Zwanenburg[1]†, David N. Jamieson[3], Andrew S. Dzurak[1] & Andrea Morello[1]



- $\nu_{e1,2} = \gamma_e B_0 \mp a_0/2$ are dependent on the *n*-spin state
- ESR does not change the *n*-spin state

→ Quantum nondemolition (QND) measurement

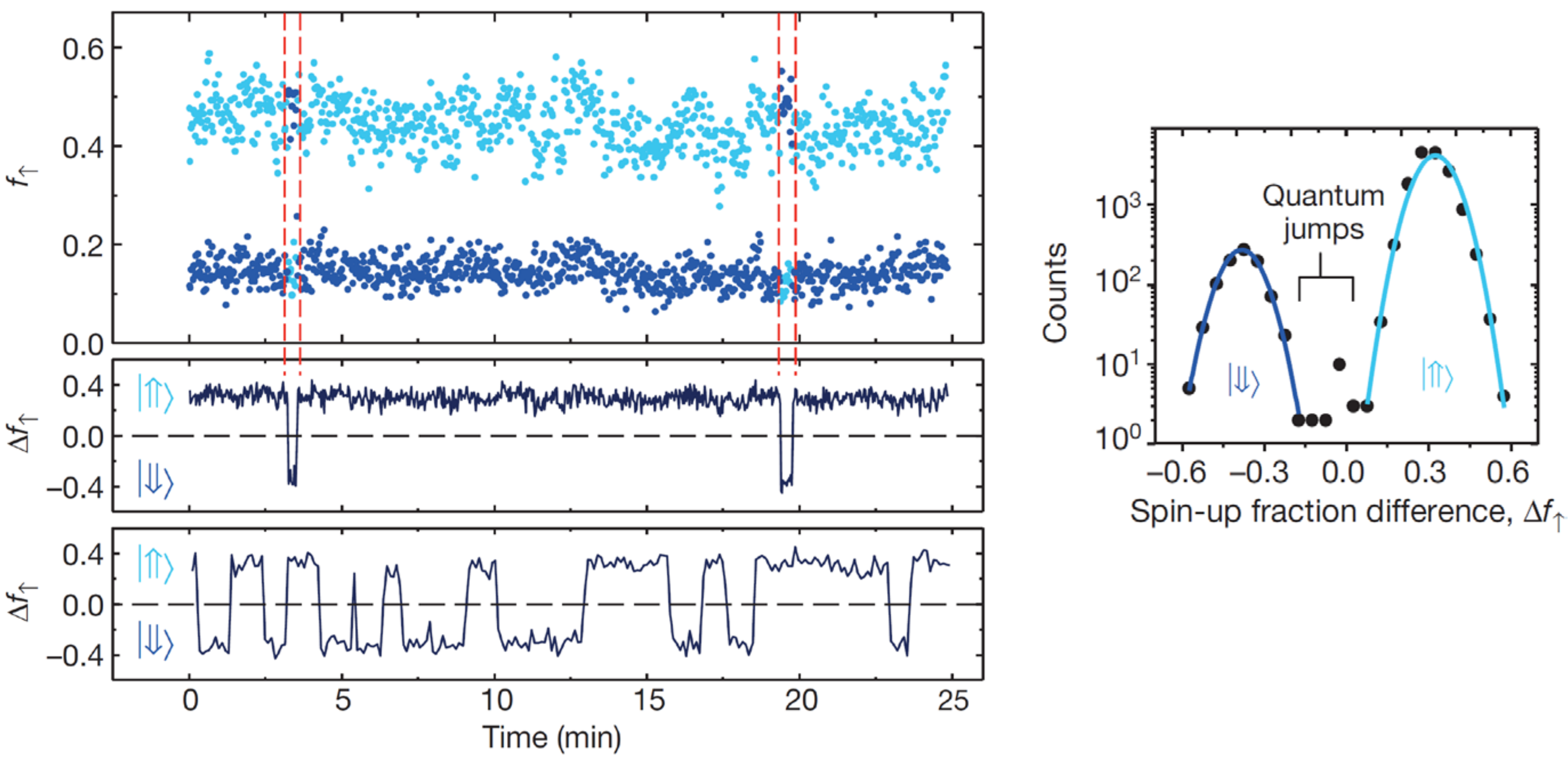
Nature **496**, 334 (2013) Pla *et al.*

LETTER

doi:10.1038/nature12011

High-fidelity readout and control of a nuclear spin qubit in silicon

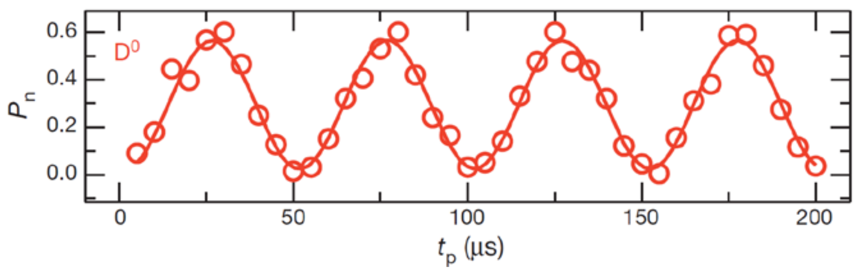
Jarryd J. Pla[1], Kuan Y. Tan[1]†, Juan P. Dehollain[1], Wee H. Lim[1]†, John J. L. Morton[2], Floris A. Zwanenburg[1]†, David N. Jamieson[3], Andrew S. Dzurak[1] & Andrea Morello[1]



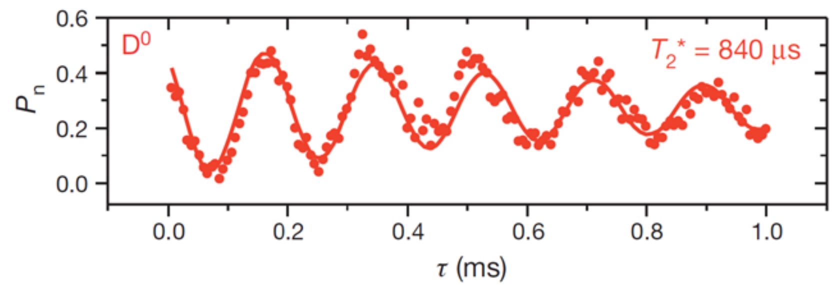
Nature **496**, 334 (2013) Pla *et al.*

Single nuclear spin under control

Rabi

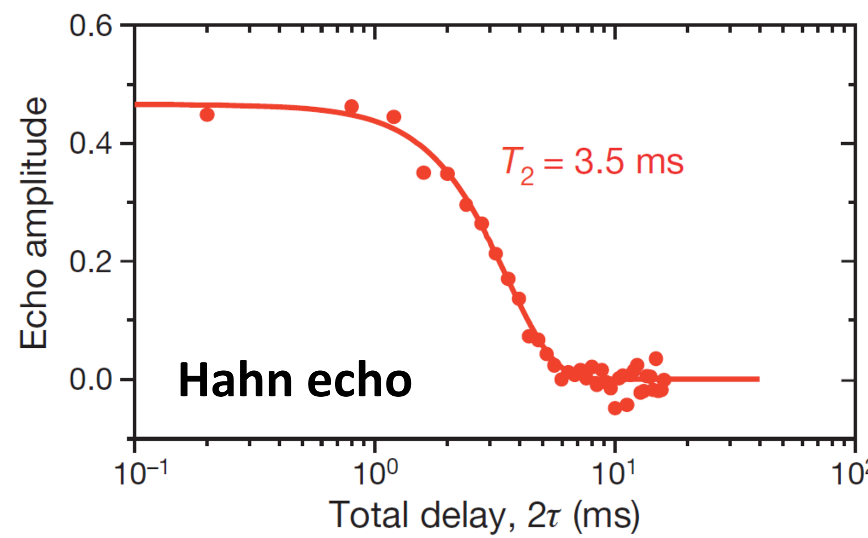


Ramsey



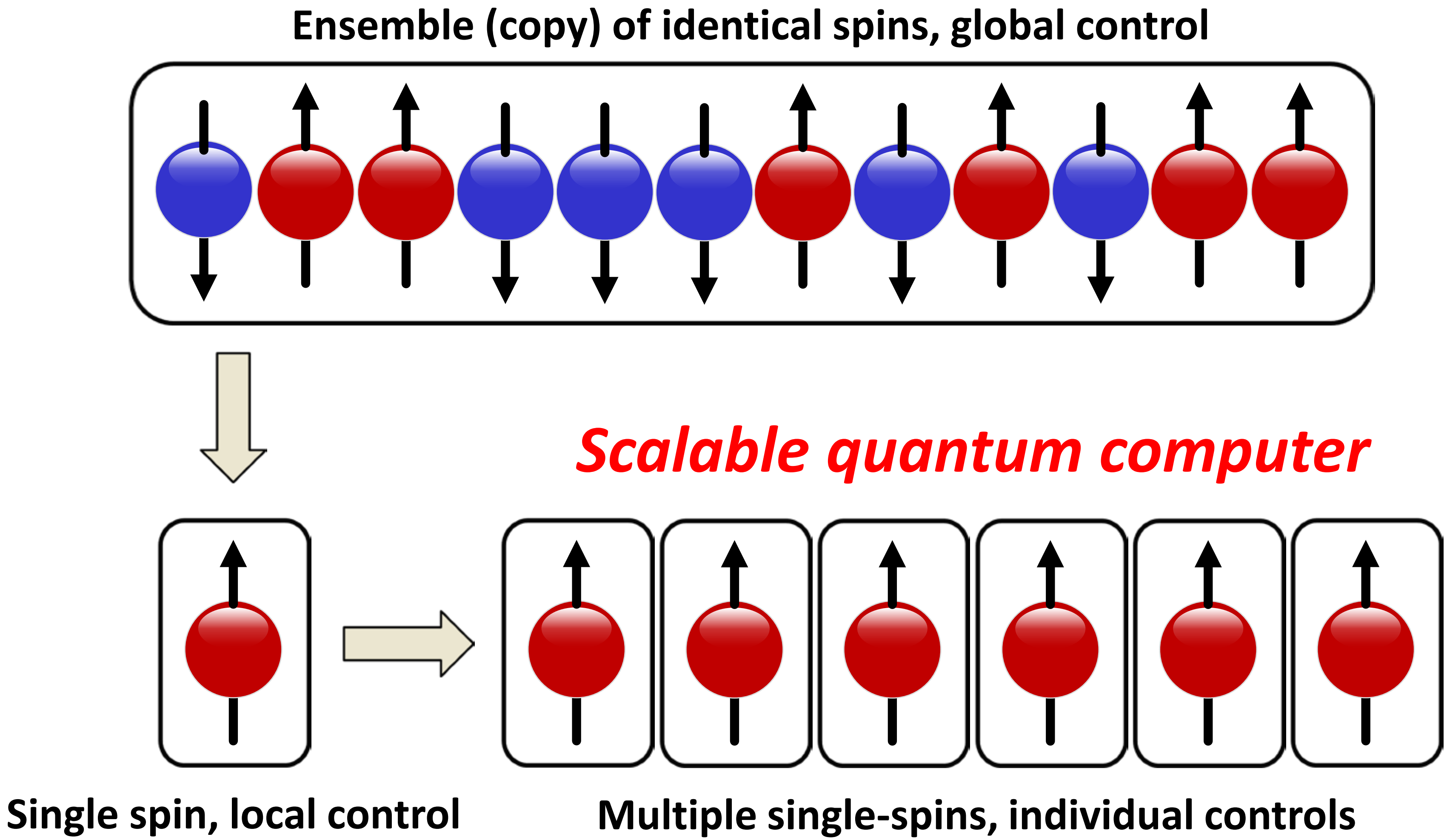
DiVincenzo's criteria

- × Qubit array
- ○ Initialization
- ○ Coherence
- △ Quantum gates
- ○ Measurement



Nature **496**, 334 (2013) Pla *et al.*

Ensemble to single, single to...



DNP in quantum computing

- **Molecule**
  - Preparation of **pseudo-pure states** costs resources exponentially, deeming NMR QC non-scalable.
  - **HBAC** is a quantum information theoretic approach to DNP.
- **Phosphorus donor in silicon**
  - **Pulsed ENDOR**, a well-established technique for population transfer, is a quantum gate operation.
  - **Single nuclear spins** can be read out non-destructively. The real challenge is how to scale up the system.