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Christian Scheller

PHYSICAL REVIEW X **10**, 011060 (2020)

Coherence of a Driven Electron Spin Qubit Actively Decoupled from Quasistatic Noise

Takashi Nakajima,[1,*,**] Akito Noiri,[1,**] Kento Kawasaki,[2] Jun Yoneda,[1,‡] Peter Stano,[1,2,3] Shinichi Amaha,[1] Tomohiro Otsuka,[1,§] Kenta Takeda,[1] Matthieu R. Delbecq,[1,¶] Giles Allison,[1] Arne Ludwig,[4] Andreas D. Wieck,[4] Daniel Loss,[1,5] and Seigo Tarucha[1,†]

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Hyperfine Bottleneck (in GaAs)

- Fluctuating nuclear spins in GaAs: ^{75}As, ^{69}Ga, ^{71}Ga , all of them 3/2 nucl. spin
- Hyperfine interaction $\Rightarrow$ eff. B-field (overhauser field) seen by electrons

How to resolve the problem?

- Eliminate nuclear spin (change material), e.g. isotopically purified Si
- Electrons (s-type) → Holes (p-type) $\Rightarrow$ reduced Hyperfine
- Polarize all nuclear spins $\Rightarrow$ no fluctuations left
- Stabilize Overhauser field by DNP $\Rightarrow$ no fluctuations left
- Echo sequences to decouple from slowly varying Overhauser field
- Adjust RF frequency to include present nuclear polarization (this paper)

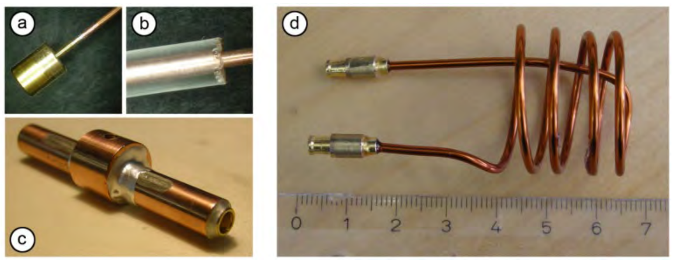
GaAs nuclear spins: RDNMR

Resistively detected NMR

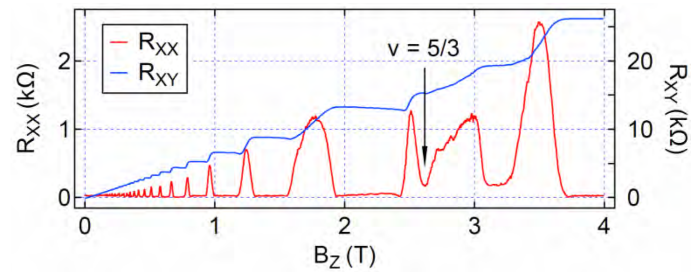
- RF coil: Scramble up thermodynamic nucl. pol. (no pumping)
- FQHE for detection (no pick up coil):

  Overhauser field → Zeeman term (no orbital effects, ν given by B_{ext})

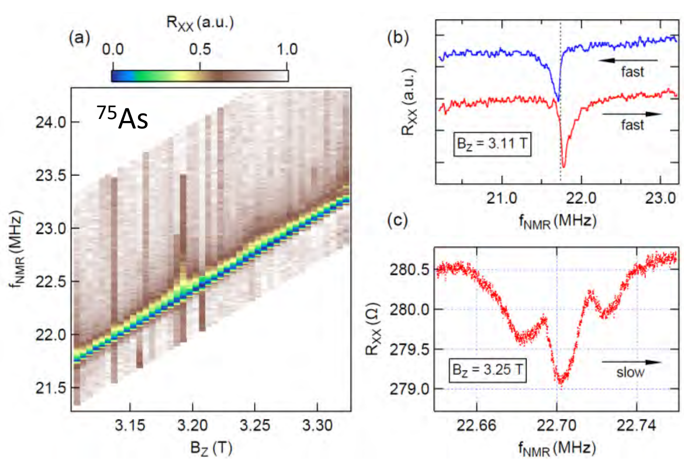
  Onset of R_{xx} peaks (quasiparticle excitation) given by B_{tot} $\Rightarrow$ depends on nucl. pol.



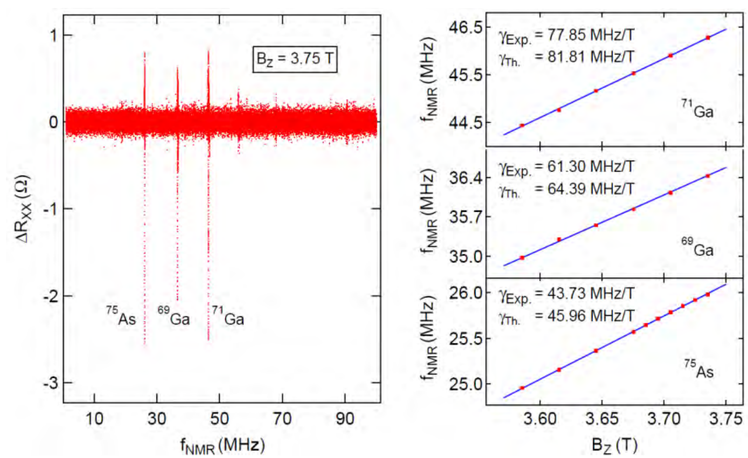
Impedance matched thermalizer & RF coil



(Fractional) Quantum Hall effect (pick up)



^{75}As resonance with quadrupolar splitting

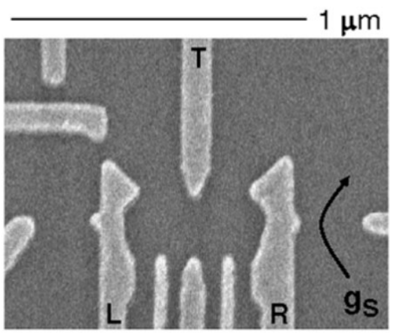


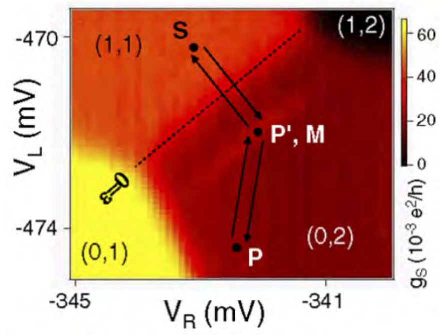
Identify all GaAs nucl. spin species: ^{75}As, ^{69}Ga, ^{71}Ga

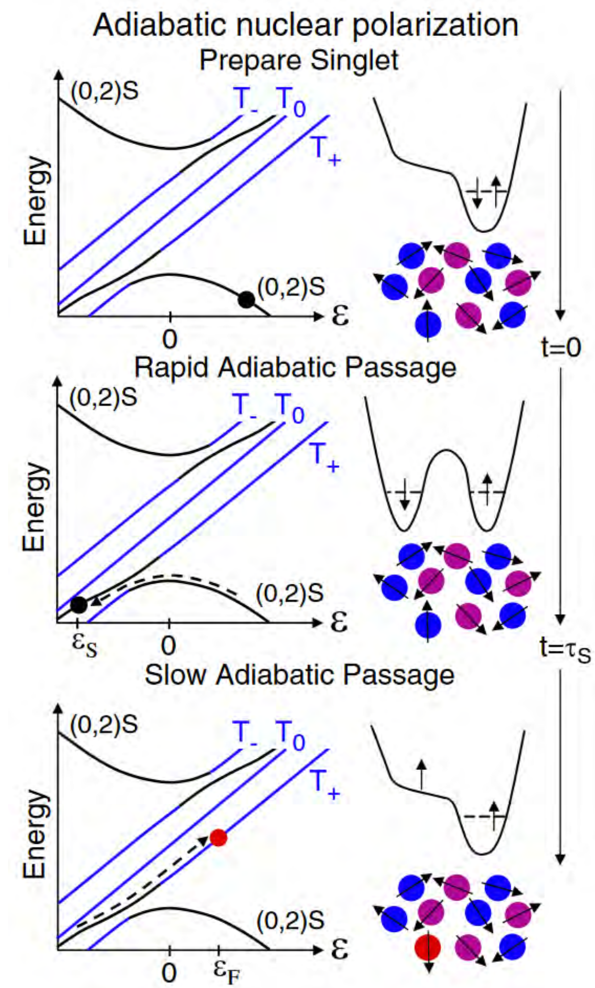
C.P.Scheller, PhD thesis (2014)

Pumping nuclear spins

- Pumping nucl. Polarization: Electron-nuclear spin flip-flop process
- Ingredients: Hyperfine gap, Landau Zener tunnelling







- GaAs double quantum dot
- QPC charge sensor

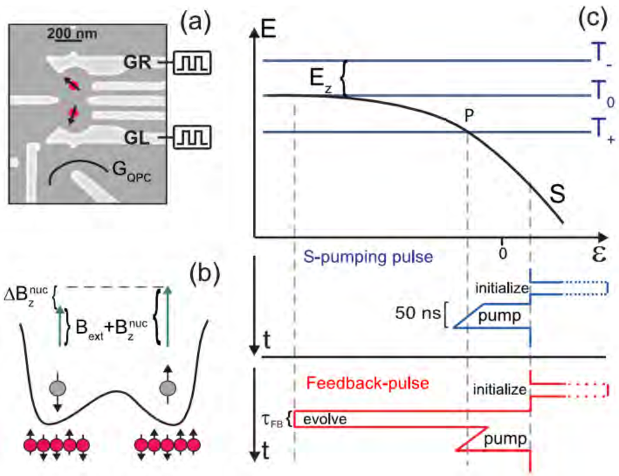
3-stage pumping cycle generating single flip-flop

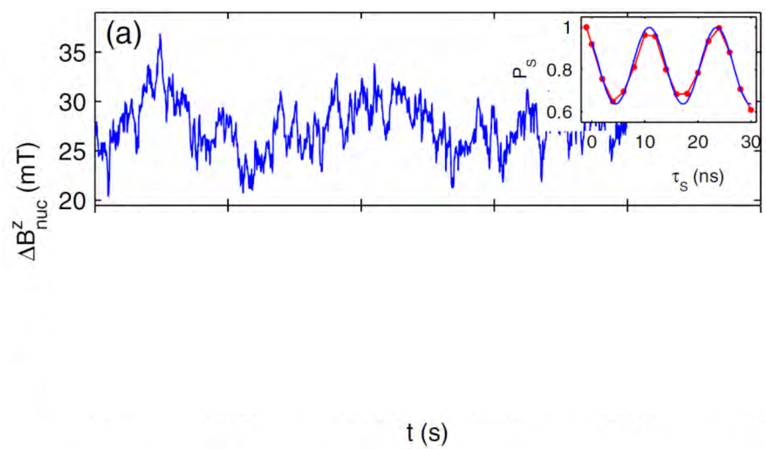
1. Initialize S(0,2) singlet
2. Rapid adiabatic passage in 1ns (Landau Zener): S(0,2)→S(1,1)
3. Slow adiabatic passage in 100ns: S(1,1)→T+ (flip flop process)
4. Unload and reinitialize S(0,2)

J. R. Petta et al., Phys. Rev. Lett. **100**, 067601 (2008)

Stabilizing nuclear spins using DNP

- GaAs double quantum dot: S-T_0 qubit
- ΔB_Z^{nuc} leads to S-T_0 oscillations $\rightarrow$ extract ΔB_Z^{nuc} from frequency (at $\varepsilon \ll 0$)





Probing nuclear field gradient ΔB_Z^{nuc}:

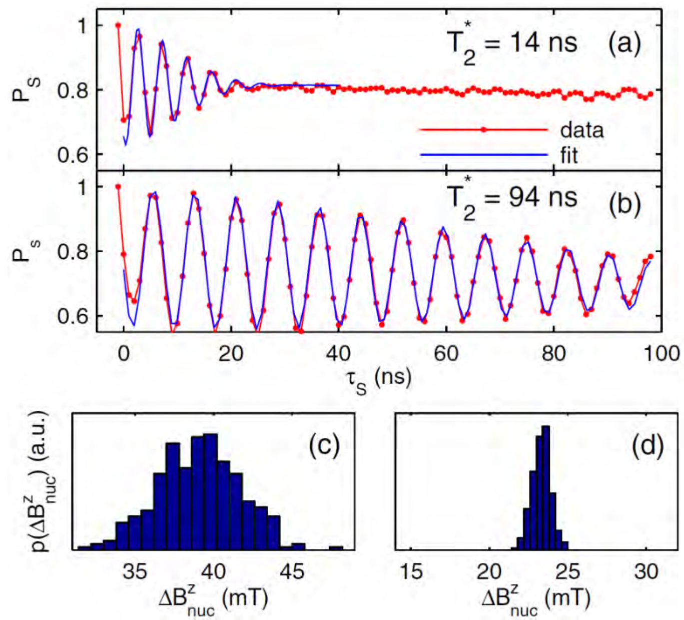
- Initialize S(0,2), fast pulse to S(1,1)
- Wait: S-T_0 oscillations
- Pulse back to start and see if S(0,2) is recovered

Pumping

- Prepare S(T^+), sweep though S-T^+ transition
  $\rightarrow$ build up (reduces) pol. with respect to B_{ext}
- Imbalance in pol. rates of dots leads to ΔB_Z^{nuc}

Stabilizing polarization

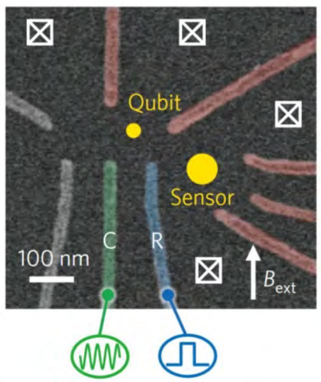
- Strong narrowing of ΔB_Z^{nuc} distribution and increase in T_2



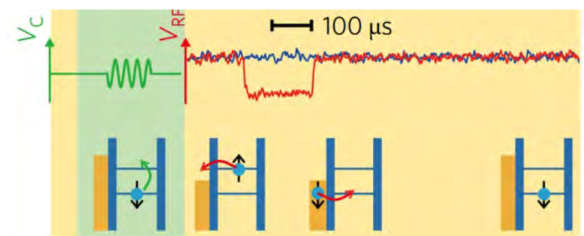
H. Bluhm et al., Phys. Rev. Lett. **105**, 216803 (2010)

Dynamical decoupling pulses

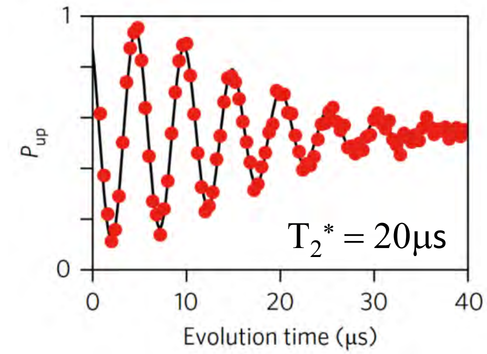
- Purified Si/SiGe QD
- EDSR (micromagnet)



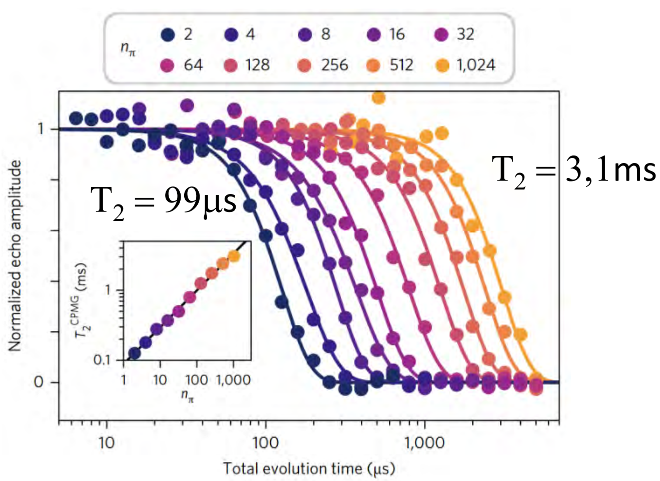
- Elzerman readout
- Q=888 from Rabi



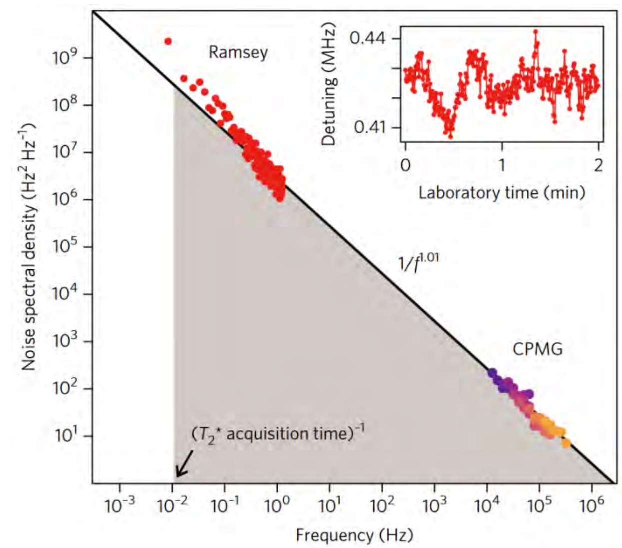
- Ramsey interference
- $\pi/2_X \rightarrow \tau_R \rightarrow \pi/2_X$



- CPMG decoupling: $\pi/2_X \rightarrow \pi_Y \rightarrow \pi/2_X$
- Gate fidelity: X 99.941%, others similar



- Extracted noise power spectral density
- 1/f noise over 7 decades ! **Limiting qubit**



J. Joneda et al., Nature nanotech. **13**, 102 (2010)

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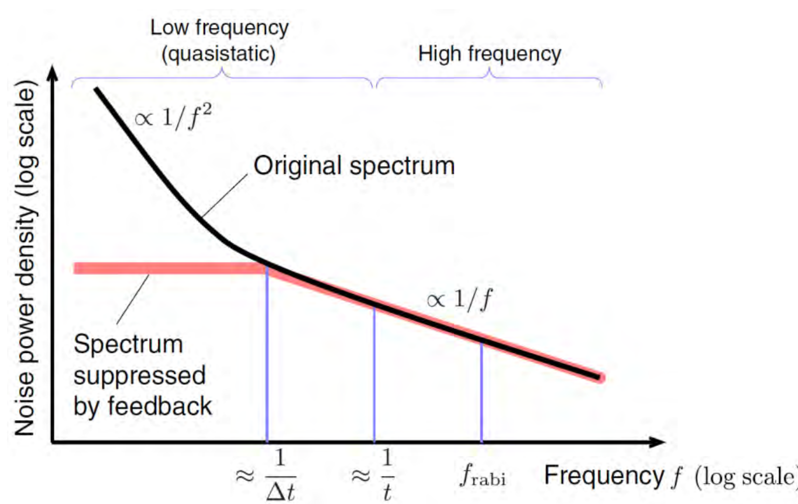
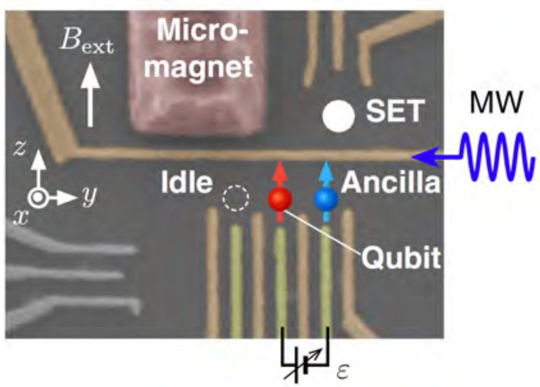
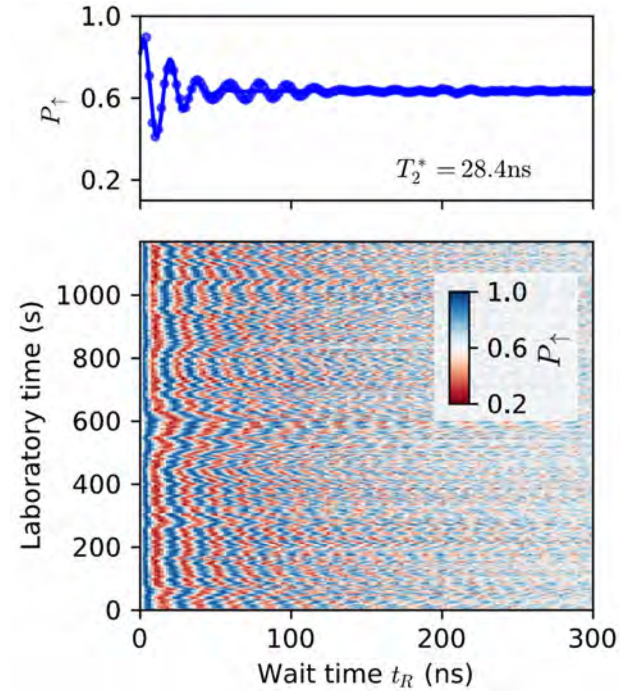
- Suppress low freq. noise by freq. feedback
- Limiting coherence factor in GaAs
- Caused by nucl. spins fluctuations $1/f^2$



Device & Ramsey measurements

- GaAs tripple quantum dot Ti/Au gates
- Micromagnet → field gradient → individually addressable spins
- Left dot: Decoupled (unused)
- Middle dot: Qubit
- Right dot: Ancilla (initialization & readout)



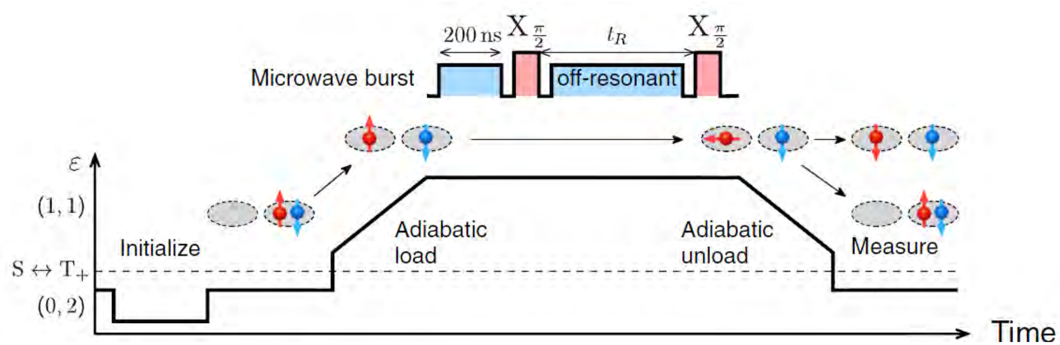


Rabi oscillations:

- Initialize “S(0,2)”, rapid passage to “S(1,1)”
- MW burst time tb
- Measure return-probability to “S(0,2)” vs tb

Ramsey:

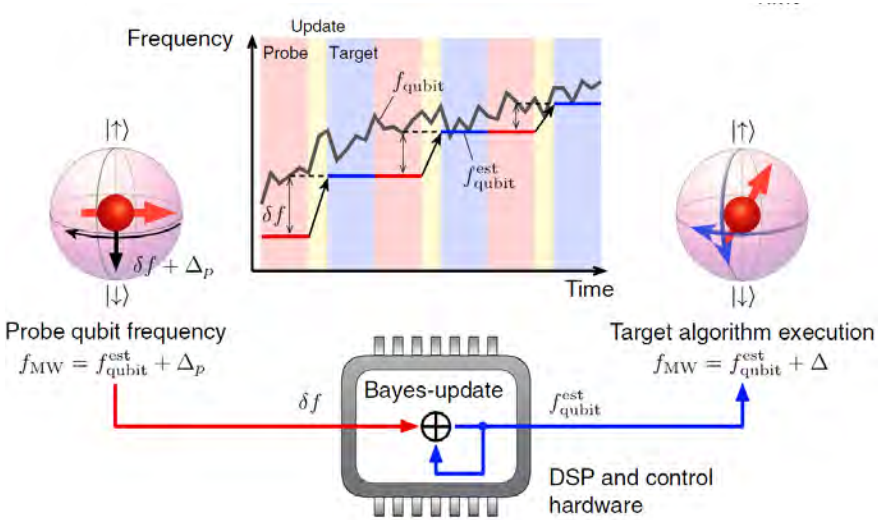
- Apply $1/4f_{rabi}$ pulse ($\pi/2$) wait t_R, apply $\pi/2$
- f_{ramsey} fluctuates due to Overhauser field
- Averaging gives reduced T_2^*=28ns

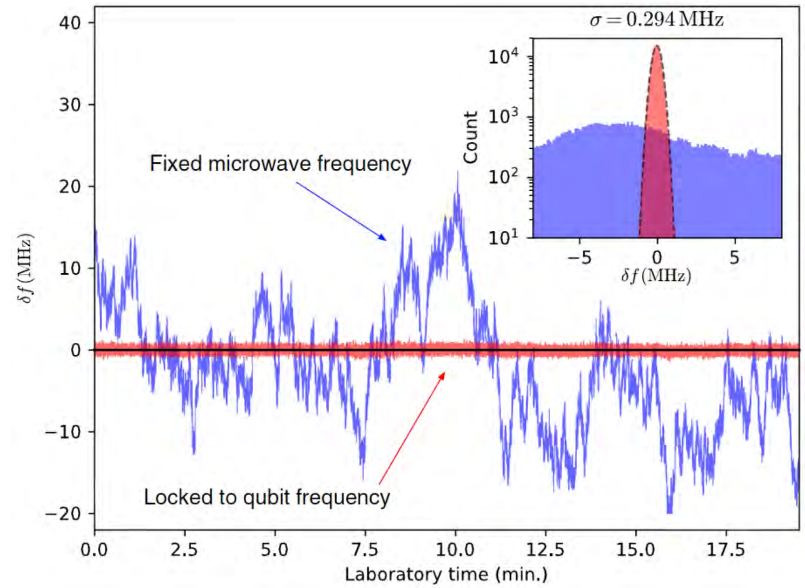


T. Nakajima et al., Phys. Rev. X **10**, 011060 (2020)

Feedback loop

- Use fluctuating ramsey oscillation as a feedback for qubit frequency (estimate B_{tot})



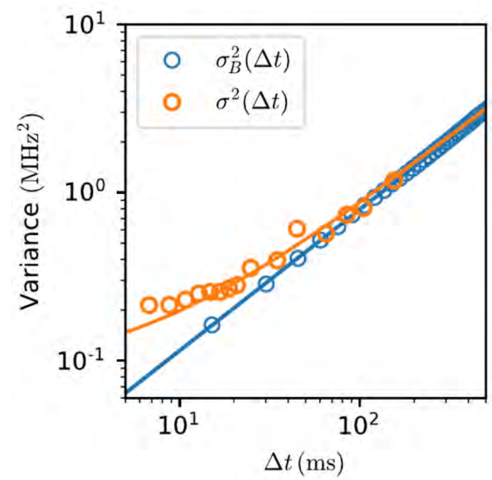


Probe stage:

- 150 samples (t_R=2,4,...,300ns)
- Set $f_{MW}=f_q^{est}+\Delta_p$ (Δ_p=50MHz, larger than nucl. fluctuations)

Target stage:

- Set $f_{MW}=f_q^{est}+\Delta$ (Δ=0 means qubit should be on resonance)
- Perform whatever measurement
  - e.g. Ramsey (set Δ=50MHz)
  - e.g. Rabi (set Δ=0MHz)



- Narrowing scales with latency of feedback $\rightarrow$ study noise spectrum
- Limited by freq. Bins of 0.25MHz ($\cong$ saturation of orange fit)

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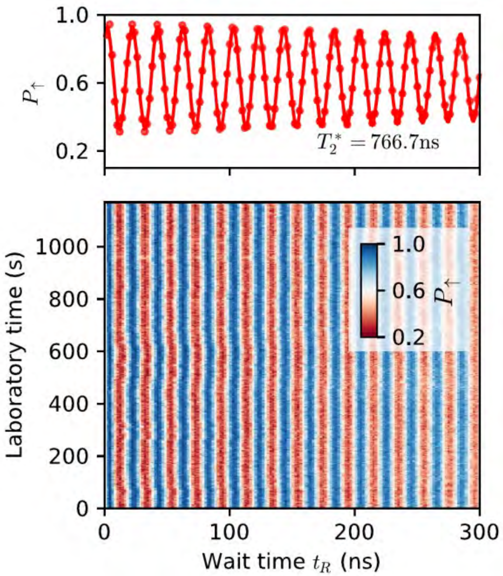
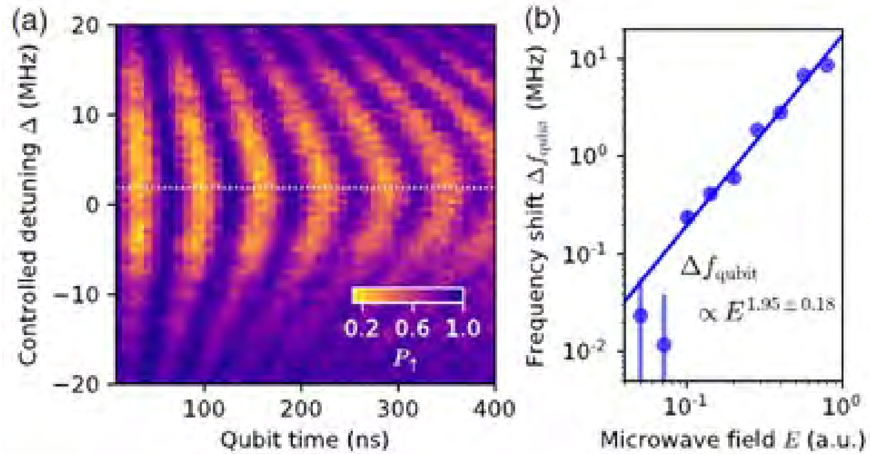
Performance with Feedback

Ramsey interference (off resonance)



Robust fringes, T_2^*=767ns (before 24ns)

Rabi oscillations (on resonance)



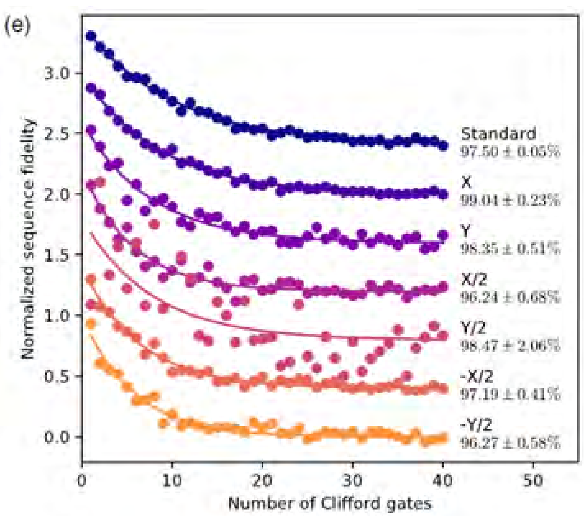
Stable chevron Rabi pattern, but symmetry off?
Dispacement scaling with E-field squared

E-field shift:

- Probe (Ramsey) without RF
- Measurement (Rabi) with drive (E-field)
  $\rightarrow$ destroys the Feedback
- Solution: Use off-resonant MW bursts

Benchmarking:

- Gates X, Y, X/2, Y/2, -X/2, -Y/2 with fidelity of 96-99%
- X gate fidelity: 99.04 %



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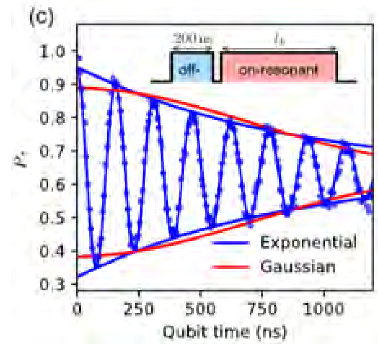
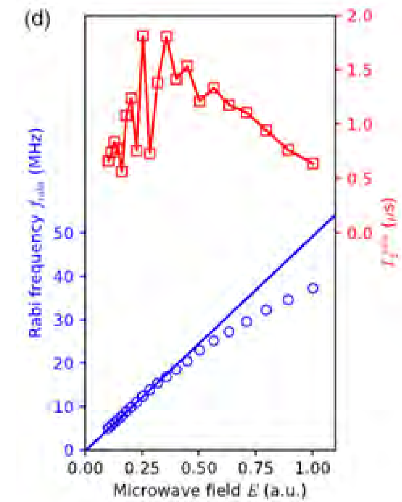
Spectral noise & limitations

Spectral noise from Rabi decay

- Rabi with feedback: Exponential decay envelope (typical for e.g. Si but not for GaAs)
- If dominated by high frequency noise, $S(f_{Rabi})$ can be calculated from T_2^{Rabi}
- Change MW power to change $f_{Rabi} \Rightarrow$ Map out S(f)



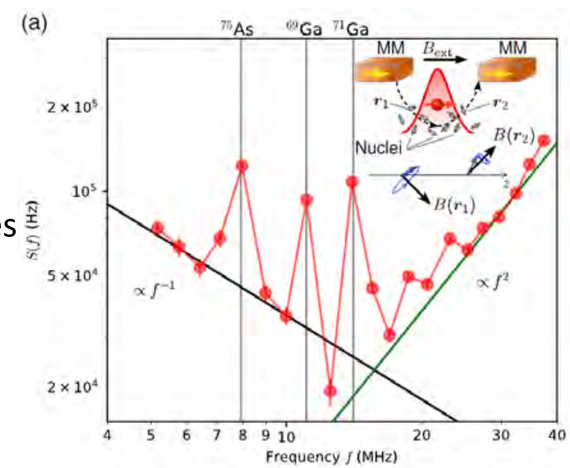


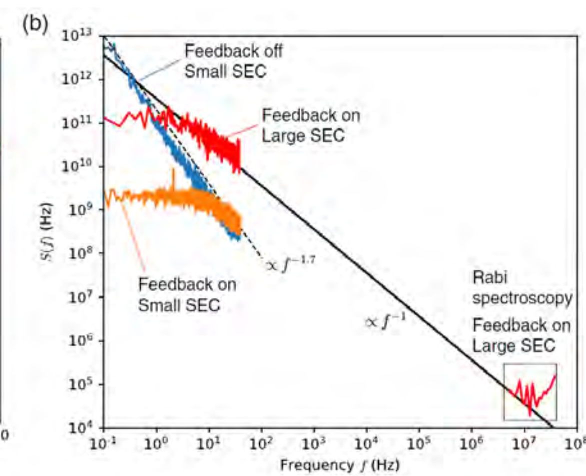
Spectral noise: 2 regimes & spectral lines

- >20MHz: S(f) increases $\sim f^2$, possibly heating due to strong drive
- <20MHz: S(f) decreases $\sim 1/f$, quasi-static noise
- Noise peaks at nuclear Lamor frequencies (MM stray field $\Rightarrow B_{eff}$ not parallel to B_{ext})

Residual charge noise

- S(f) scales with interdot coupling (SEC)
- Large SEC & Feedback: Recover S(f) $\sim$ 1/f as for e.g. Si devices
- Charge noise possibly limited by MM





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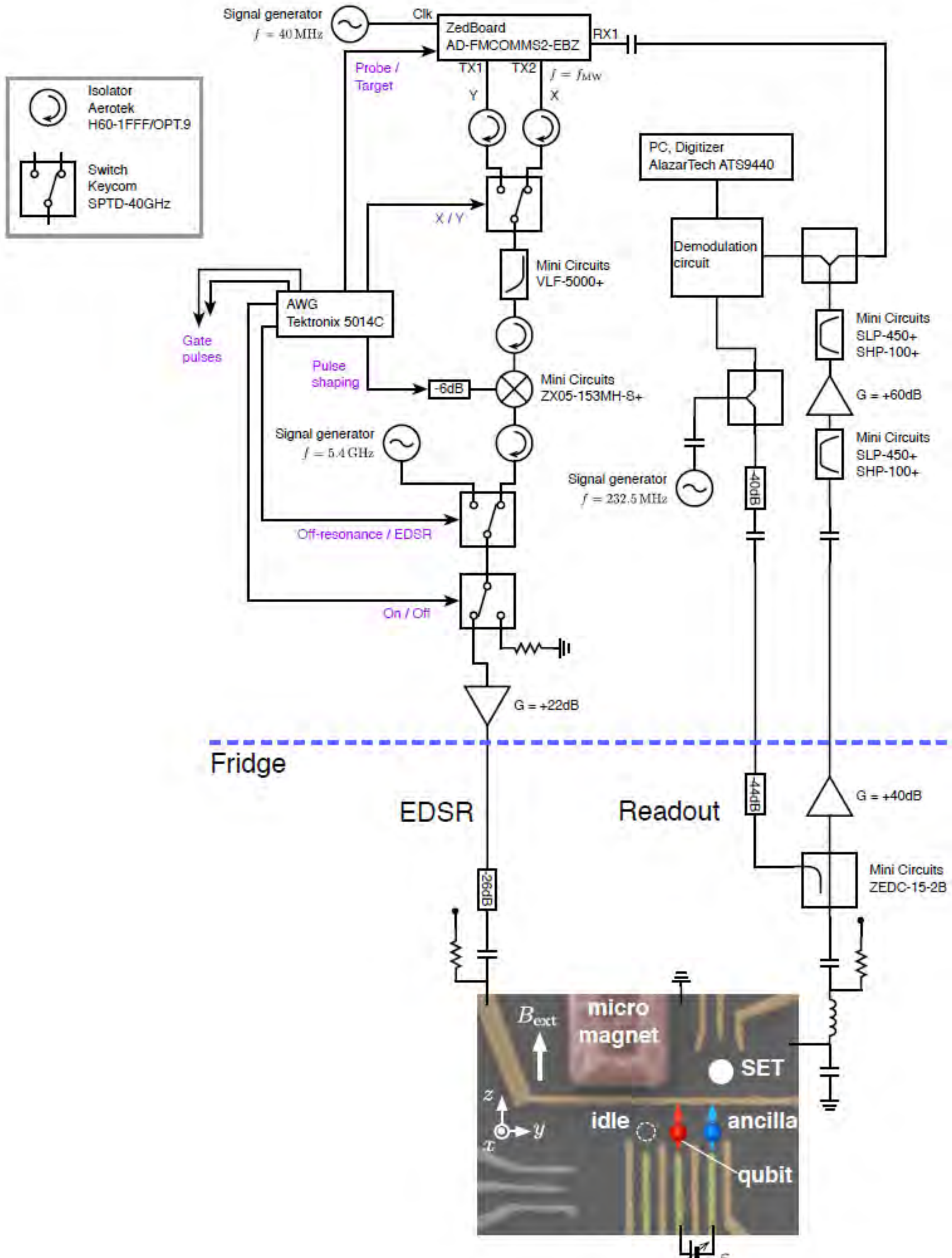
Summary

- Hyperfine field from nucl. spins can be limiting qubit coherence
- Material systems without nuclear spins or purified exist, e.g. ^{28}Si, here charge noise dominates giving $S(f) \sim 1/f$
- Nuclear spins can be decoupled:
  DNP (stabilize nuclear polarization)
  CPMG and other decoupling pulses
  Feedback using Hamiltonian estimation (this paper)
- Decoupling latency (frequency) can be used to study noise spectrum S(f)
- Charge noise seems to be dominating in GaAs as well after decoupling nuclear spins ($S(f) \sim 1/f$ recovered)


Signal generator
$f = 40\,\mathrm{MHz}$
Clk
ZedBoard
AD-FMCOMMS2-EBZ
RX1
TX1
TX2
$f = f_{\mathrm{MW}}$
Y
X
Probe / Target
Isolator
Aerotek
H60-1FFF/OPT.9
Switch
Keycom
SPTD-40GHz
PC, Digitizer
AlazarTech ATS9440
X / Y
Demodulation circuit
Mini Circuits
VLF-5000+
AWG
Tektronix 5014C
Gate pulses
Mini Circuits
SLP-450+
SHP-100+
Pulse shaping
-6dB
Mini Circuits
ZX05-153MH-S+
G = +60dB
Signal generator
$f = 5.4\,\mathrm{GHz}$
Mini Circuits
SLP-450+
SHP-100+
Signal generator
$f = 232.5\,\mathrm{MHz}$
-40dB
Off-resonance / EDSR
On / Off
G = +22dB
Fridge
EDSR
Readout
-44dB
G = +40dB
Mini Circuits
ZEDC-15-2B
-26dB
B_{ext}
micro magnet
SET
idle
ancilla
qubit
z
y
x
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