arXiv:1306.2720

Coherence and Screening in Multi-Electron Spin Qubits

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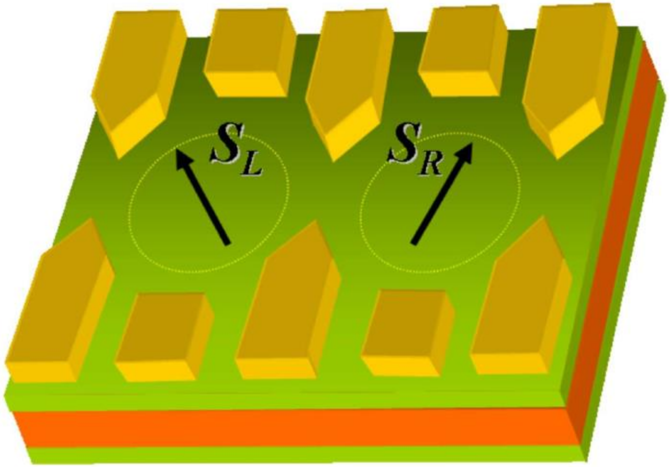
Journal Club, 18 June 2013

Quantum Computation with Spins in QDs



D. Loss and D. P. DiVincenzo,
Phys. Rev. A **57**, 120 (1998)

$S_{L,R}$: **Spin 1/2**

e.g.:
- Spin of single electron
- Multi-electron state with effective spin 1/2

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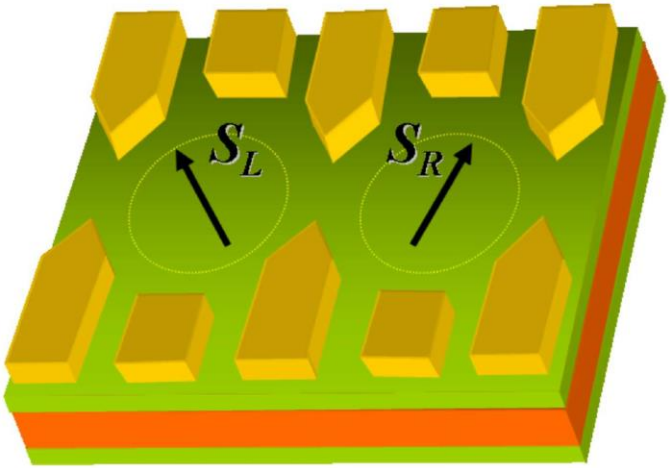

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Advantage of multi-electron spin qubits:

Upscaling to a large number of qubits may become **architecturally less challenging**

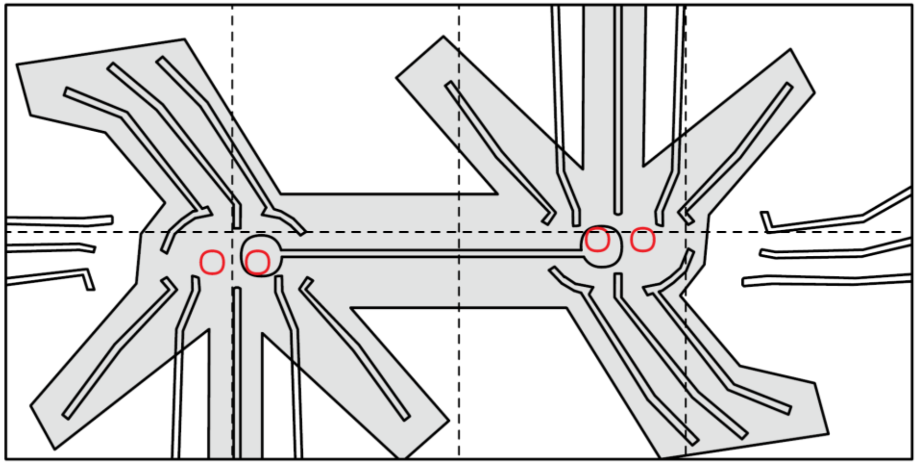

Figure from Trifunovic *et al*., Phys. Rev. X **2**, 011006 (2012)

Single- or Multi-Electron Spin Qubits?

“Multi-electron QDs have also received theoretical attention due to ease of realization as well as **possibly improved performance**.”

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Hu and Das Sarma,
PRA **64**, 042312 (2001)

Effective Hamiltonian for multi-electron case mostly much more complicated than for **single electrons**.

Barnes *et al.*,
PRB **84**, 235309 (2011)

Multi-electron spin qubits less sensitive to charge noise due to screening.

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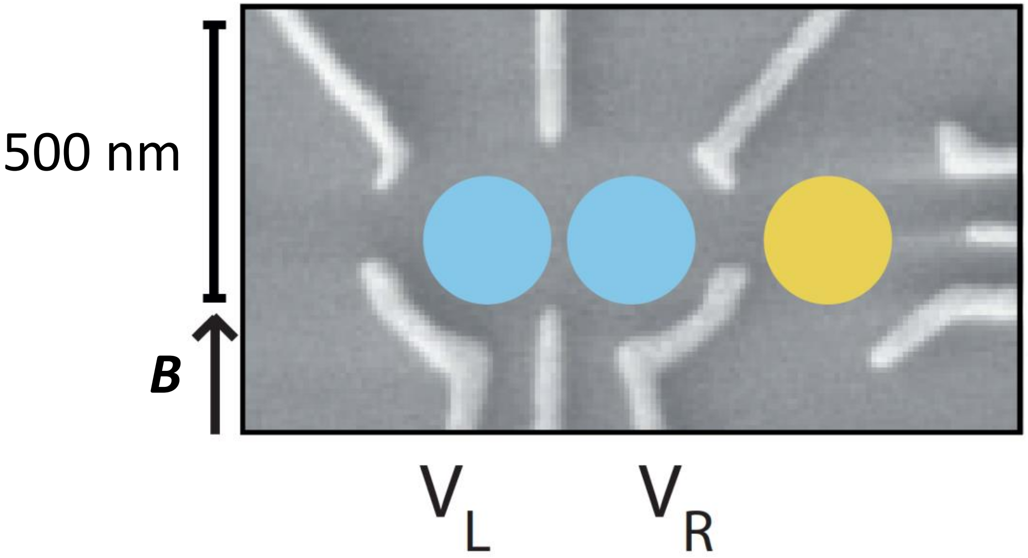
→ **Multi-electron** spin qubits less sensitive to charge noise due to screening.

Higginbotham *et al.*:

Compare exchange oscillations in coupled single-electron QDs to those in coupled multi-electron QDs (same device).

Setup

GaAs heterostructure



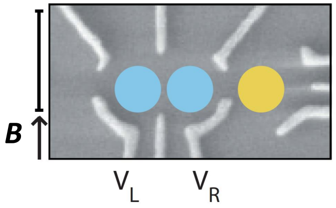
Detuning: $\varepsilon \propto (V_\mathrm{L} - V_\mathrm{R})$

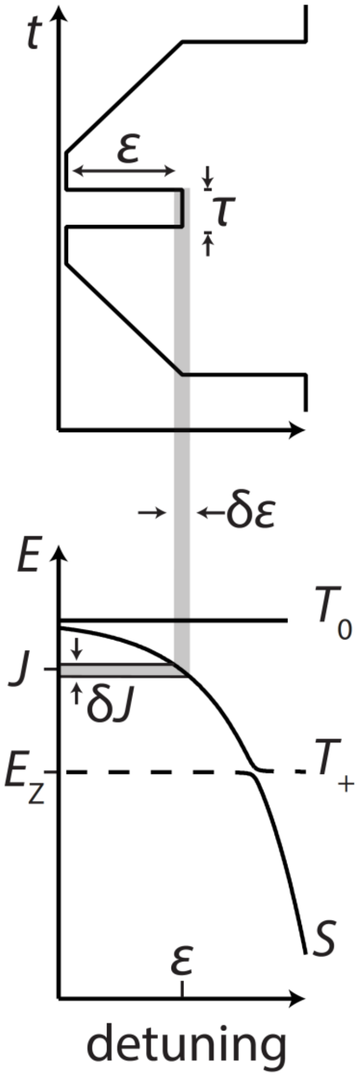
Two charge configurations

(1,1) and (7,5)

B = 200 mT　　　　B = 50 mT

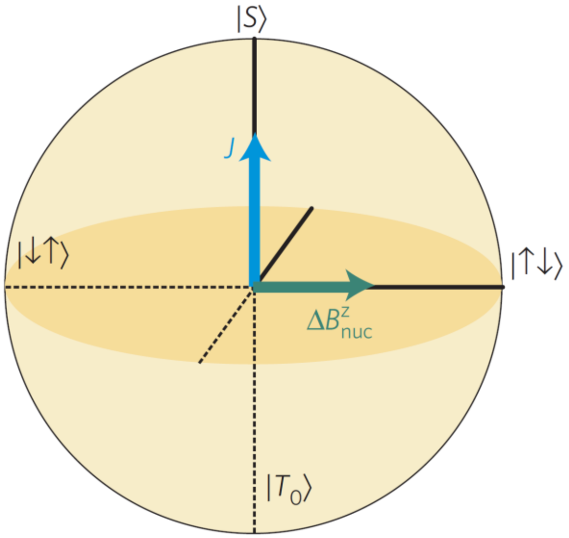
Pulse Sequence





Bloch sphere for two-qubit system:

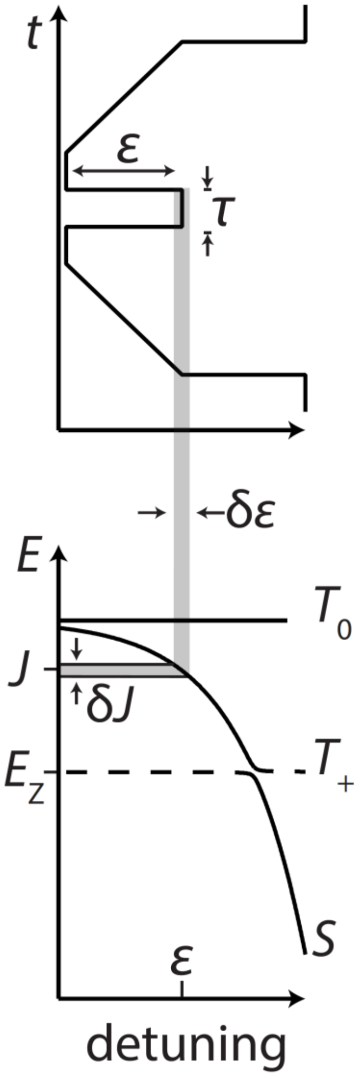
$$|S\rangle = \frac{|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle}{\sqrt{2}}$$



$$|T_0\rangle = \frac{|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle}{\sqrt{2}}$$

Figure from Foletti *et al.*, Nat. Phys. 2009

Pulse Sequence



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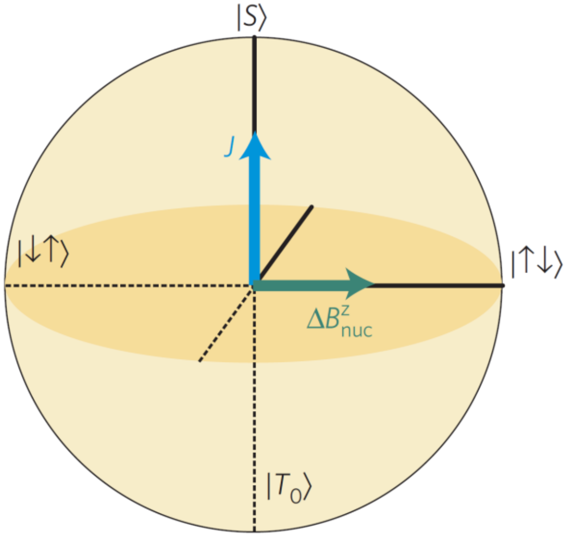

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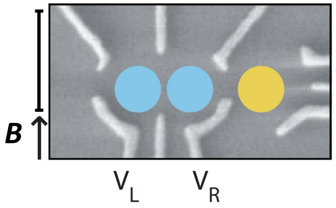


Read out:
Singlet probability

Average over different *J*

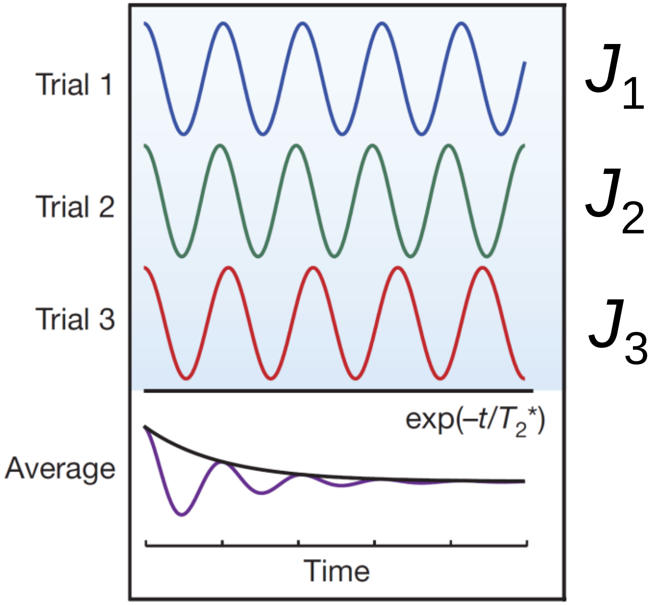
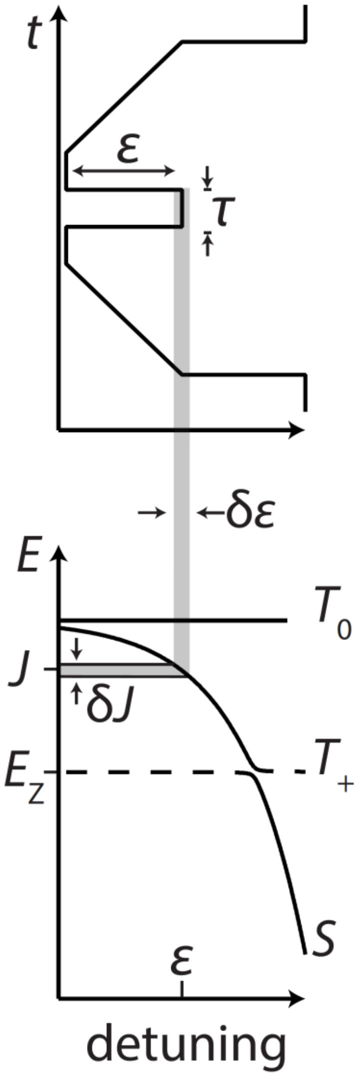
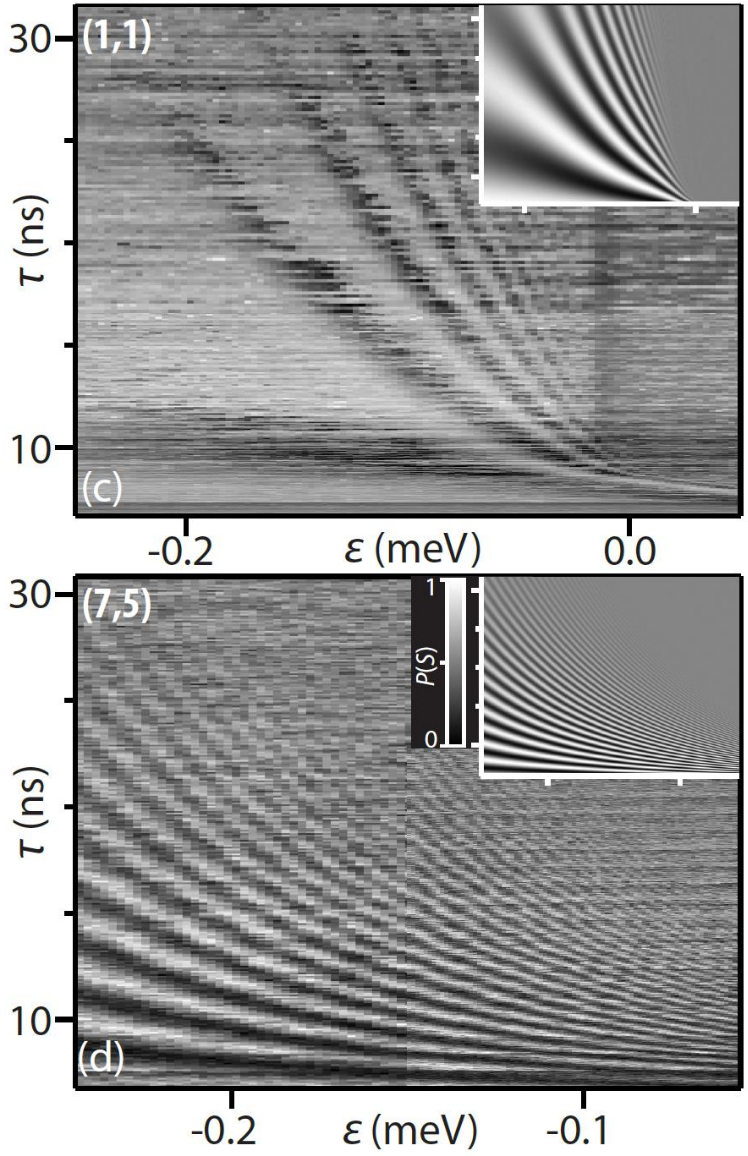
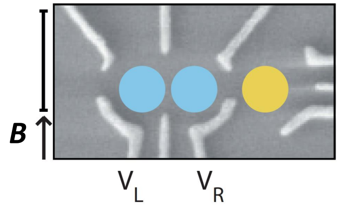


Figure from Ladd *et al.*, Nature 2010

Pulse Sequence







Multi-electron case

Oscillations are faster (< 1 ns)

Less dephasing

Data Analysis

Fit function: $\exp[-(\Gamma\tau)^2]\cos(2\pi J\tau + \phi)$

“Phase shift ϕ can arise from bandwidth limits in the apparatus”

$\Gamma = 1/T_2^*$: Dephasing rate

$Q = J/\Gamma$: Quality factor,
number of oscillations during T_2^*

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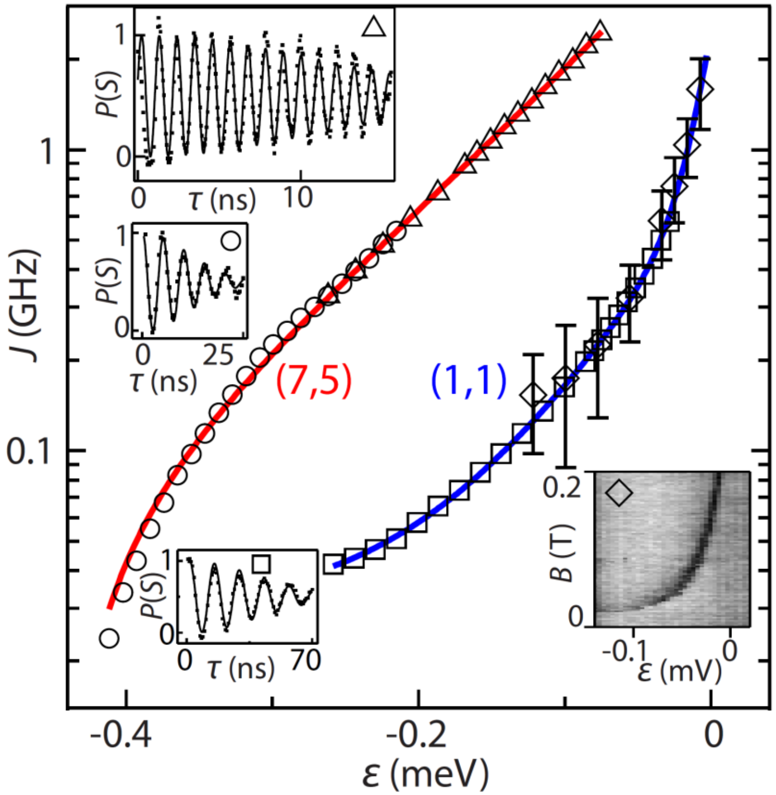
Results for *J*:

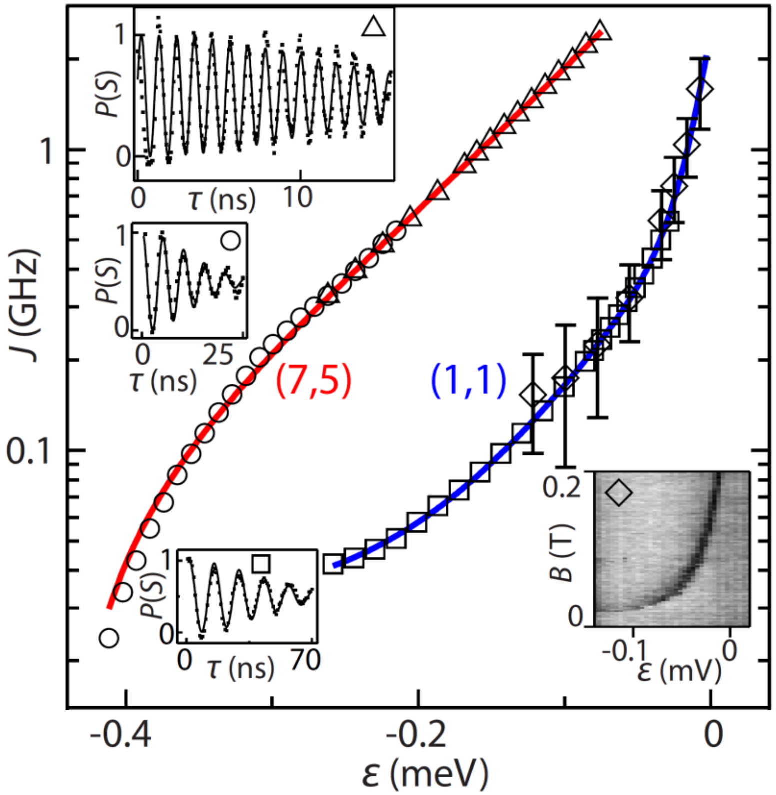


Data Analysis

Fit for $J(\varepsilon)$: $$J = J_0 + J_1 e^{k_1 \varepsilon} + J_2 e^{k_2 \varepsilon}$$

	J_0 (GHz)	J_1 (GHz)	J_2 (GHz)	k_1 (meV^{-1})	k_2 (meV^{-1})
(1,1)	0.029	0.61	0.85	15	59
(7,5)	-0.42	0.70	5.5	1.34	12

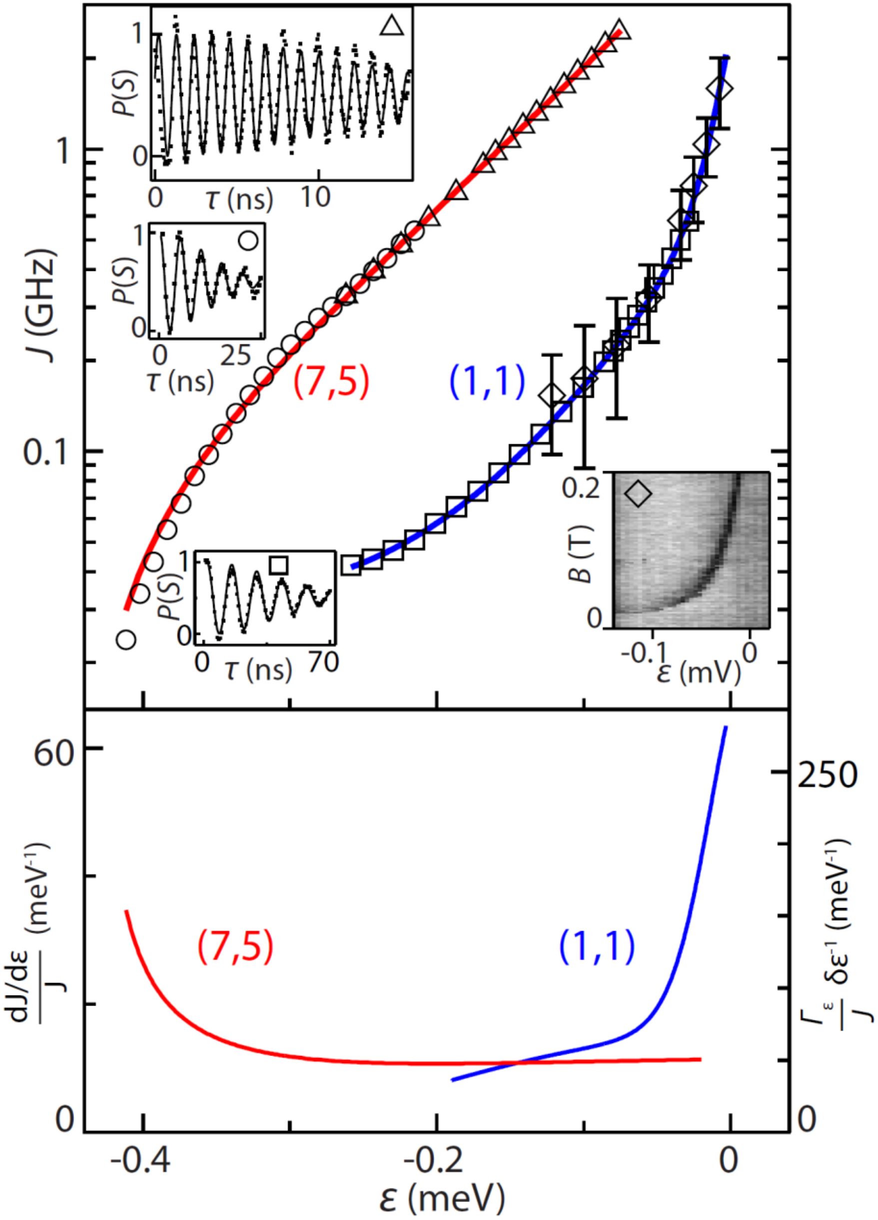
Results for *J*:



Data Analysis

Results for *J*:

Derivative/*J*:



Noise Model – Electrical Noise

Assume quasistatic electrical noise (Gaussian distribution) with standard deviation $\delta\varepsilon$:

$$\Gamma_{\varepsilon} = \frac{\mathrm{d}J}{\mathrm{d}\varepsilon}\pi\sqrt{2}\delta\varepsilon$$

Γ_{ε} : Dephasing rate due to charge noise

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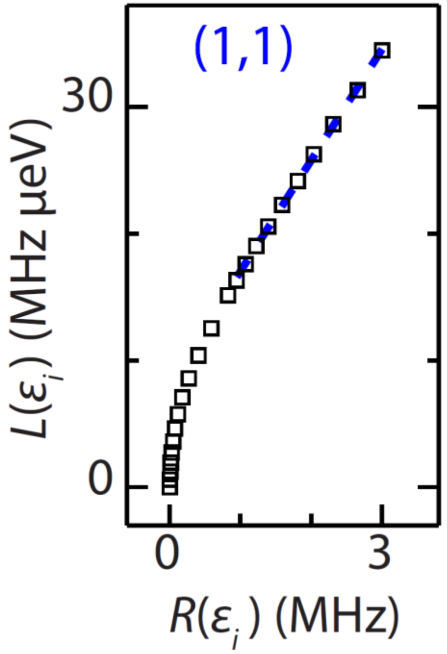
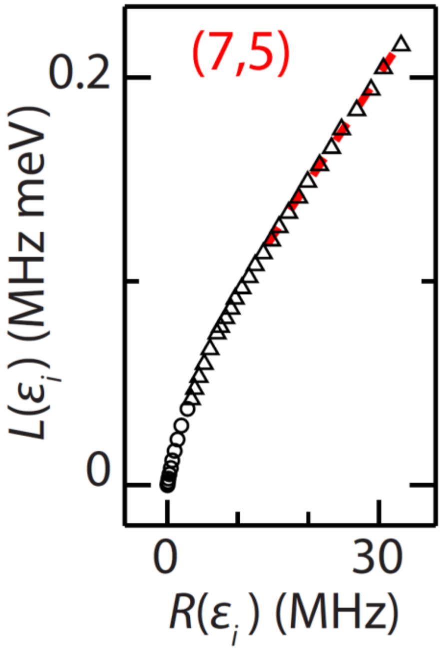
$$\underbrace{\int^{\varepsilon_i} J d\varepsilon}_{L(\varepsilon_i)} = \pi\sqrt{2}\delta\varepsilon \underbrace{\int^{J(\varepsilon_i)} Q dJ}_{R(\varepsilon_i)}$$

Noise Model – Electrical Noise

Electrical noise dominates at large *J*



$\delta\varepsilon$ = 2.0 μeV



$\delta\varepsilon$ = 1.2 μeV

If Γ = Γ$_\varepsilon$:

$$\underbrace{\int^{\varepsilon_i} J\,d\varepsilon}_{L(\varepsilon_i)} = \pi\sqrt{2}\,\delta\varepsilon \underbrace{\int^{J(\varepsilon_i)} Q\,dJ}_{R(\varepsilon_i)}$$

Noise Model – Hyperfine Coupling

Very large *J*: **Dephasing due to charge noise**

Noise Model – Hyperfine Coupling

Very large *J*: **Dephasing due to charge noise**

Very small *J*: **Dephasing due to nuclear spin fluctuations**

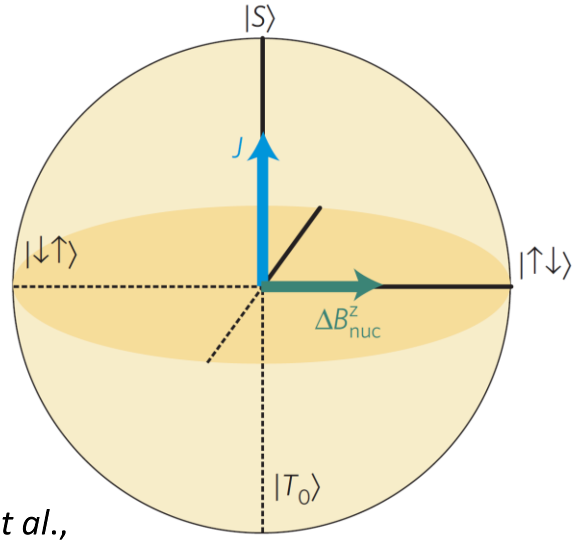
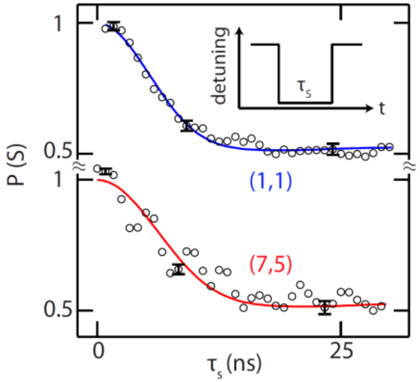
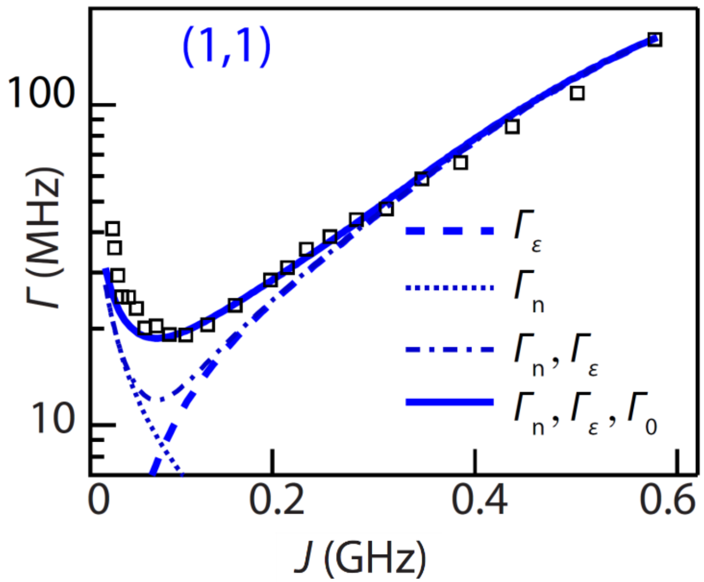


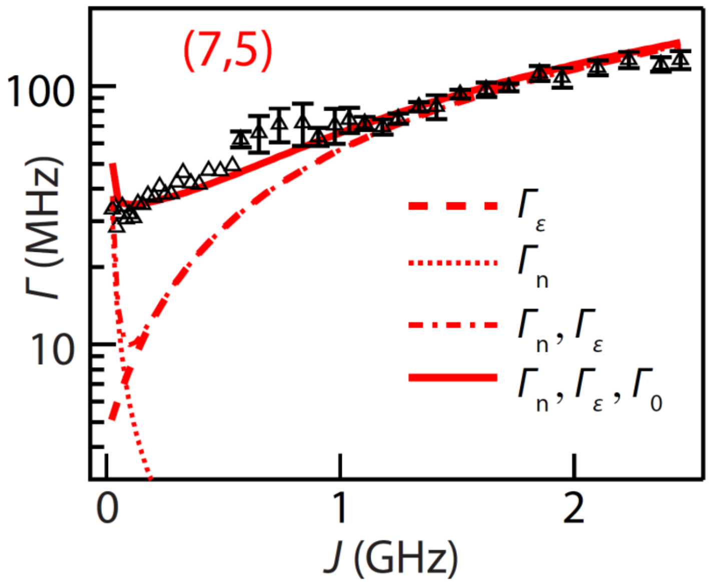
Figure from Foletti *et al.*,
Nat. Phys. 2009



For details → see paper/supplement

Dephasing: Experiment vs. Theory





Γ_ε : Electrical noise

Γ_n : Nuclear spin fluctuations

Γ_0 : Additional noise of unknown origin,
considered independent of detuning ε

Total dephasing rate: $$\Gamma_\Sigma = (\Gamma_\varepsilon^2 + \Gamma_\mathrm{n}^2 + \Gamma_0^2)^{1/2}$$

"We have verified numerically that this introduces a small error"

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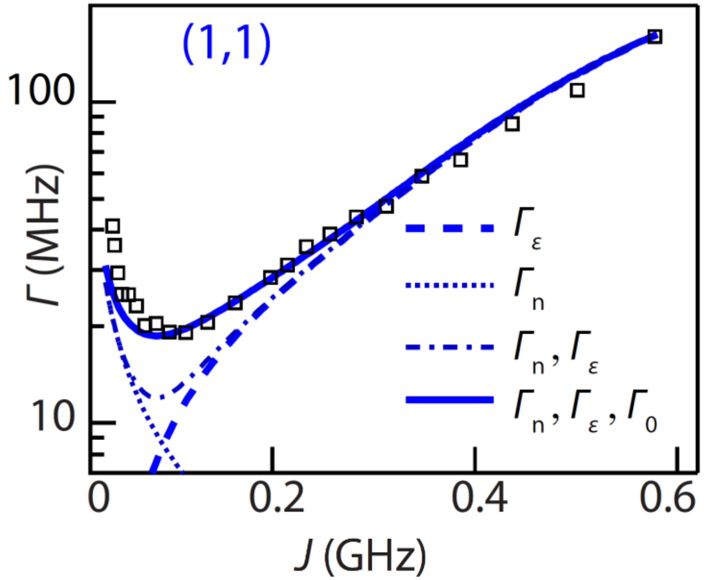

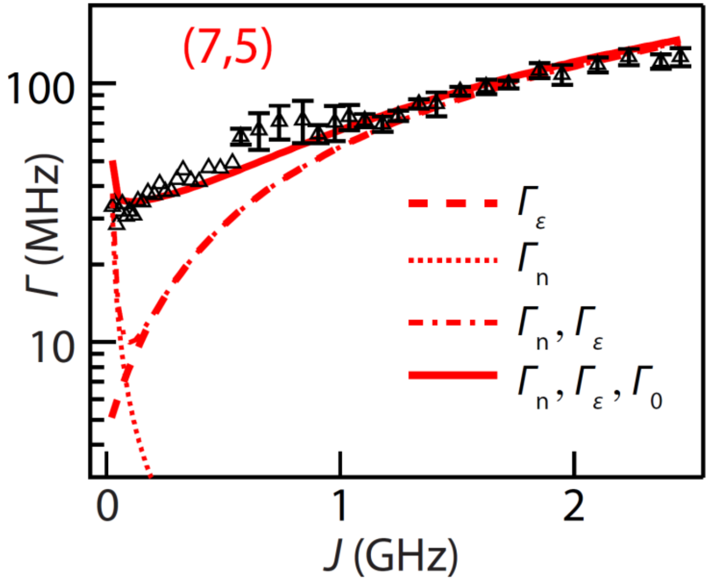

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(1,1):
$\Gamma_0 = 14$ MHz

(7,5):
$\Gamma_0 = 34$ MHz

Total dephasing rate: $$\Gamma_\Sigma = (\Gamma_\varepsilon^2 + \Gamma_n^2 + \Gamma_0^2)^{1/2}$$

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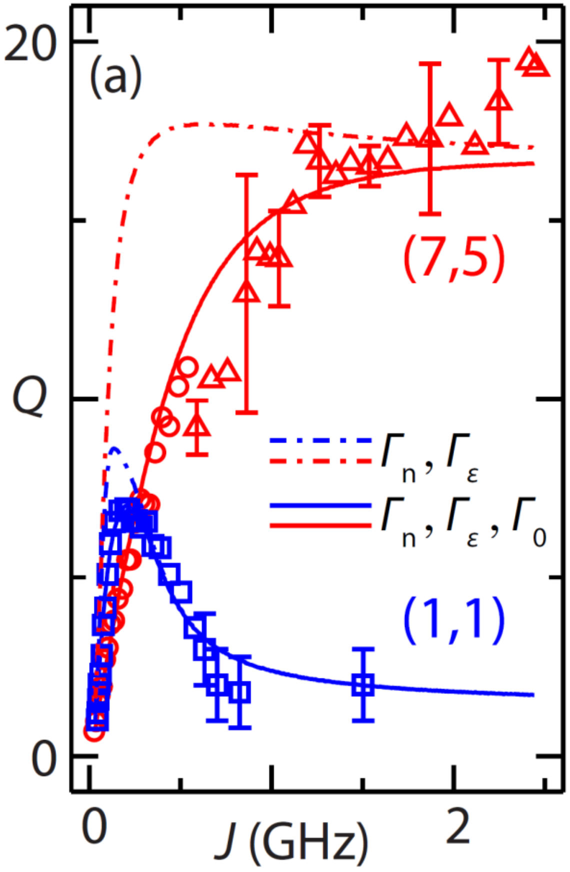
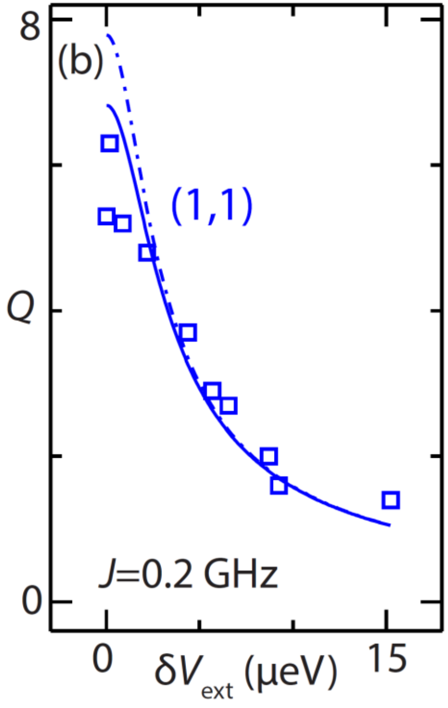
Quality Factors

Main result



Consistency check
(no free parameters)



↗
Standard deviation of
artificial electrical noise
(via two-channel arbitrary
waveform generator)

Outlook

1) **“Future studies will investigate (...) a much broader range of occupancies”**

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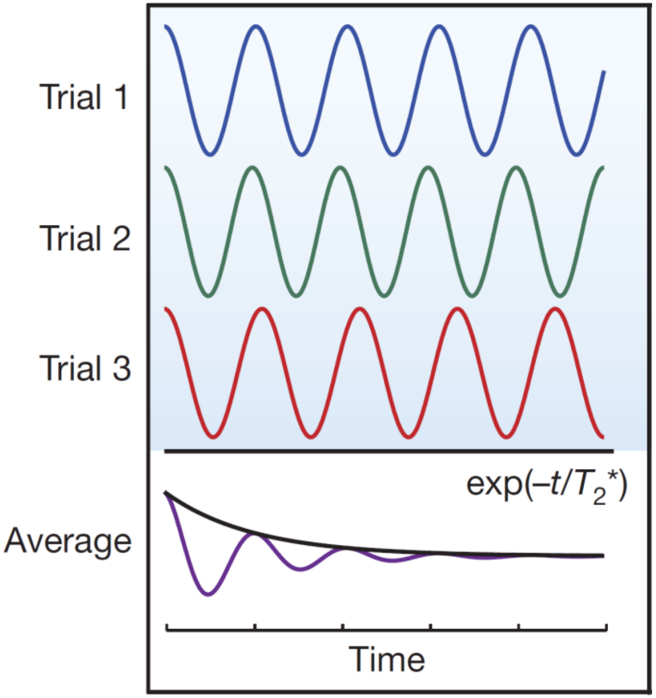
2) In this work:

- Free induction decay
- Noise considered as quasistatic

⇨ **Performance with echo pulses??**

Free Induction Decay

Average over different *J*



J_1

J_2

J_3

Figure from Ladd *et al*., Nature 2010

Dynamical Decoupling

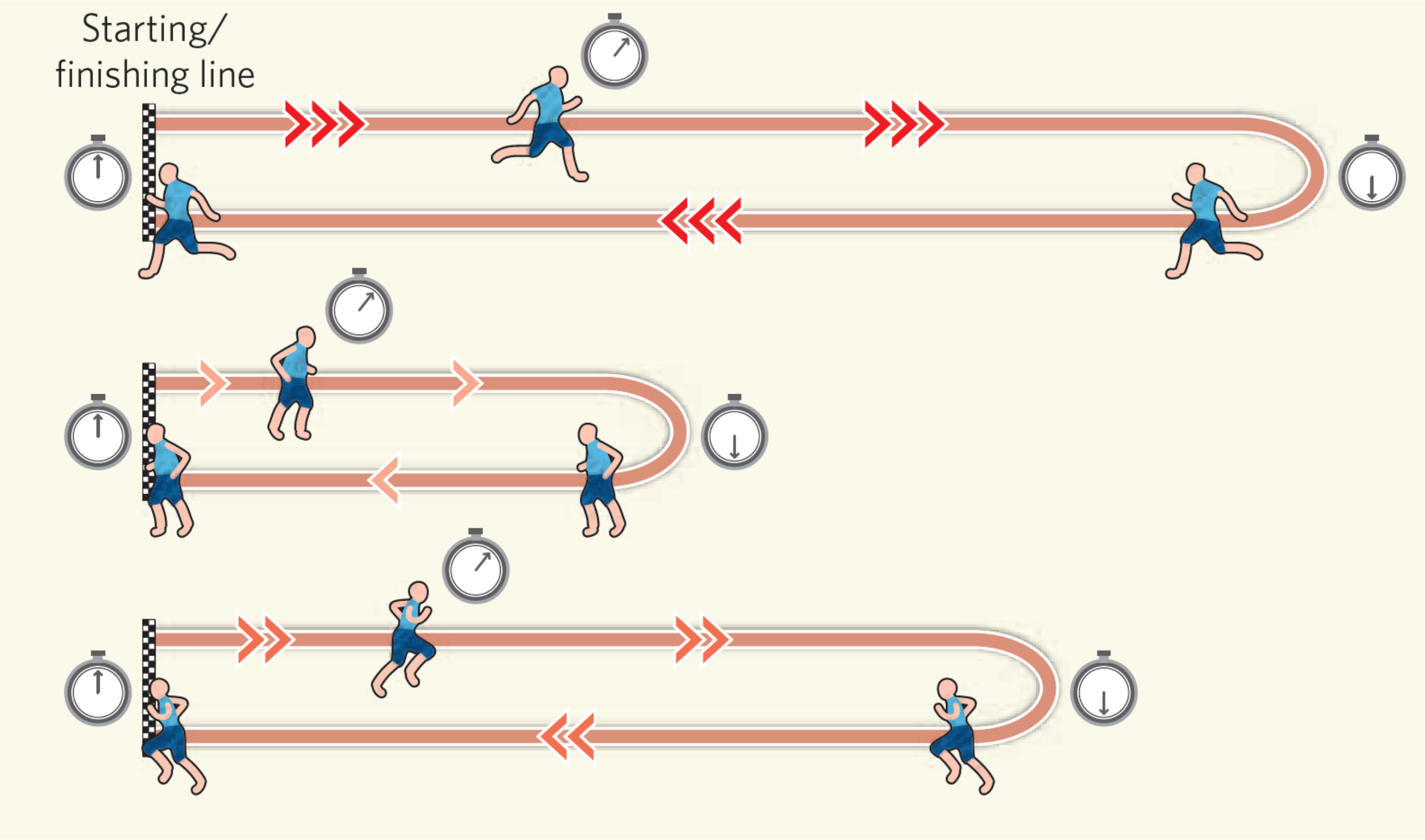


Figure from Buckley/Awschalom, Nature (News & Views) 2009

Conclusions

- Exchange oscillations in coupled QDs with occupancy (7,5) were faster than those in the (1,1) case, and had a higher quality factor (Q > 15, as opposed to Q ~ 2).

- A simple model based on quasistatic charge and hyperfine noise is in good agreement with the results.

- Additional dephasing had to be included phenomenologically for quantitative agreement at intermediate exchange energies *J.*

  > *"We speculate that the unknown dephasing source may be due to transverse electric fields effecting the tunnel coupling of the device, something that is not explicitly accounted for in the noise model."*

- Outlook:
  - Different electron occupancies
  - Dynamical decoupling