Fast quantum state preparation of spin qubits in diamond with strong microwave pulses

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Introduction: strongly driven qubits, why?

Recent experiments, e.g.

- NV-center qubits (Fuchs *et al.*, Science (2009), this talk)
- superconducting qubits (Tuorila *et al.*, ArXiv:1005.3446)

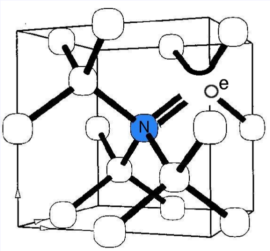
Goal in Quantum Information Processing:
the most coherent operations before decoherence

- weak pulses: same pulse area = same operation
- so increase coherence time
- and operate faster with stronger pulses

Outline

- experiment: NV-center spin qubits
- theory: qubit under strong harmonic driving
- theory: qubit state preparation with strong pulses
- proposal: for new experiments with NVs

the qubit: Nitrogen-Vacancy center spin qubit in diamond (NV^-)

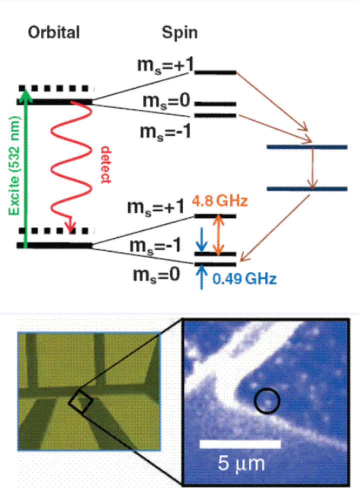


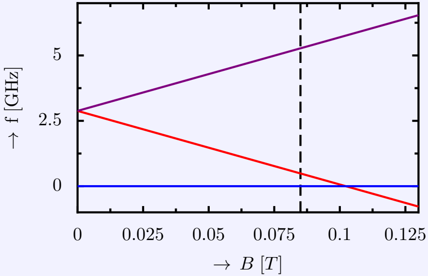
Interesting for QIP:

- single NV^-s addressable
- crystal splitting of ground state
- coherent state control
- coherence time $\simeq$ 2 ms (room temperature!)
- state initialization and readout by optical pumping

"Crystals are like people; it is only the defects that make them interesting" (J.C. Franck)

experiment: setup and level diagrams for NV^{-}

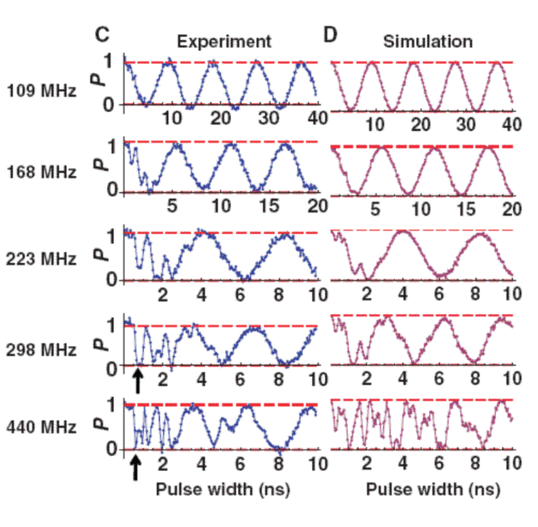




- Static external B field 0.085 T [111]
- effective 2-level system

G.D. Fuchs *et al.*, Science **326**, 1520 (2009)

experiment: dynamics



G.D. Fuchs *et al.*, Science **326**, 1520 (2009)

theory: qubit under strong harmonic driving

Time-dependent Hamiltonian with harmonic driving $V(t) = A\cos(\omega t)$,

$$H(t) = h_z(t)\sigma_z + h_x\sigma_x = \hbar \begin{pmatrix} \omega_0/2 + V(t)/2 & \Delta \\ \Delta & -\omega_0/2 - V(t)/2 \end{pmatrix}$$

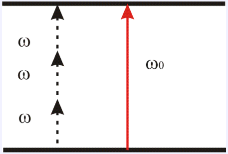
Interaction picture

$$i \begin{pmatrix} \dot{c}_1 \\ \dot{c}_0 \end{pmatrix} = \begin{pmatrix} 0 & \Delta^*(t) \\ \Delta(t) & 0 \end{pmatrix} \begin{pmatrix} c_1 \\ c_0 \end{pmatrix}$$

with interaction

$$\Delta(t) = \Delta e^{i\omega_0 t + i\frac{A}{\omega}\sin(\omega t)} = \Delta \sum_{n=-\infty}^{\infty} J_n(A/\omega) e^{i(\omega_0 + n\omega)t}$$

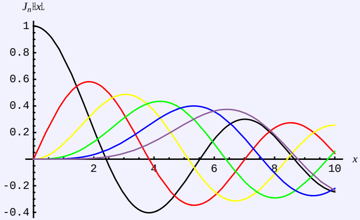
theory: resonant driving in the high-frequency limit



Assume:

1. resonant driving $\omega_0 + n_{\mathrm{res}}\omega = 0$
2. high-frequency driving: $\omega \gg \Delta$

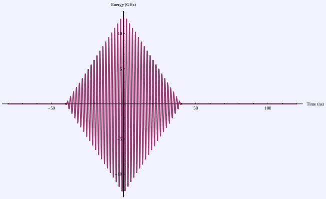
$$\Delta(t) = \Delta \sum_{n=-\infty}^{\infty} J_n(A/\omega)\, e^{i(\omega_0 + n\omega)t} \simeq \Delta J_{n_{\mathrm{res}}}(A/\omega)$$



- degenerate qubit ($\omega_0 = 0$, at 0.1 Tesla) $\Rightarrow \Delta_{\mathrm{eff}} \simeq \Delta J_0(A/\omega)$
  $\Delta_{\mathrm{eff}} = 0$: Coherent destruction of tunneling (CDT) (*)
- simple resonance ($\omega_0 = \omega$) $\Rightarrow$ $\Delta_{\mathrm{eff}} \simeq \Delta J_{-1}(A/\omega)$

(*) Grossmann *et al.*, PRL (1991)

theory: driving with strong pulses



pulse $V(t) = A(t)\sin(\omega t)$,
assumptions: $\omega\tau_p \gg 1$ and $A/\omega \ll \omega\tau_p \Rightarrow$

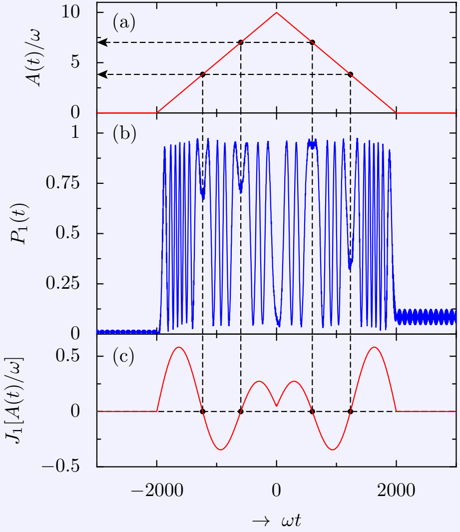
1. Effective interaction $\Delta_{\text{eff}}(t) = \Delta J_{n_{\text{res}}}[A(t)/\omega]$
2. Equation of motion

$$i\begin{pmatrix} \dot{c}_1 \\ \dot{c}_0 \end{pmatrix} \simeq \Delta_{\text{eff}}(t)\,\sigma_x \begin{pmatrix} c_1 \\ c_0 \end{pmatrix}$$

3. Solution

$$P_1(t) = \sin^2[\Phi(t)], \qquad \Phi(t) = \int_{t_0}^{t} \mathrm{d}\tau\, \Delta_{\text{eff}}(\tau)$$

Example: strong pulse with linear rise and fall



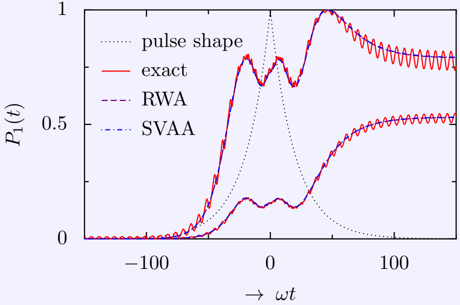
$\Delta_{\text{eff}}(t) = \Delta J_{n_{\text{res}}}[A(t)/\omega]$

- $\omega = \omega_0$ and $A_{\max}/\omega = 10$
- instantaneous Rabi frequency $\propto \Delta_{\text{eff}}(t)$
- instantaneous coherent destruction of tunneling

M. Wubs, Chemical Physics *in press* (2010)

Comparison: exact and effective dynamics (I/II)

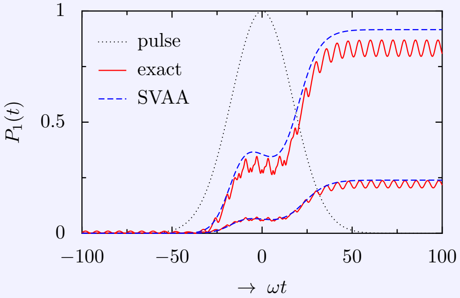
Exponential pulses, $A(t) = A \exp(-|t|/\tau_p)$



- $\omega = \omega_0$
- $A/\omega = 10$
- $\omega\tau_p = 40$
- $\Delta/\omega = 0.05$ (upper), $= 0.02$ (lower)

Comparison: exact and effective dynamics (II/II)

Gaussian pulses, $A(t) = A \exp(-t^2/\tau_p^2)$



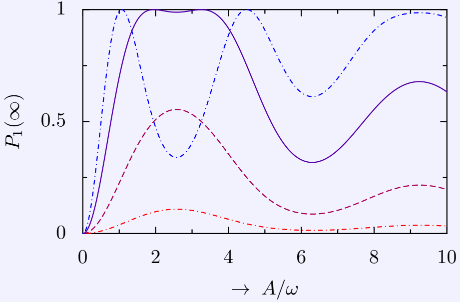
- $\omega = \omega_0$
- $A/\omega = 4$
- $\omega\tau_p = 40$
- $\Delta/\omega = 0.05$ (upper), $= 0.02$ (lower)

theory: qubit state preparation with strong pulses

Many pulse shapes $A(t)$ may lead to same intended final state (e.g. $|1\rangle$)

$$P_1(\infty) = \sin^2[\Phi(\infty)], \qquad \Phi(\infty) = \int_{t_0}^{\infty} \mathrm{d}\tau\, \Delta_{\mathrm{eff}}(\tau) = \Delta \int_{t_0}^{\infty} \mathrm{d}\tau\, J_{n_{\mathrm{res}}}[A(\tau)/\omega]$$

Weak coupling, $\omega = \omega_0 \Rightarrow \Phi(\infty) \propto$ pulse area



- gaussian pulses
- $\omega\tau_p = 20$ (red), 50, 100, and 150 (blue)
- $\Delta = 0.02\omega$
- shortest pulse that inverts qubit: $\Delta\tau_p = 1.12$ for $A/\omega = 2.66$

Conclusions/proposal: new experiments with NVs

1. Experiments by Fuchs *et al.*: strongly pulsed single NV qubits
2. Here: accurate effective dynamics in high-frequency regime
3. Coherent destruction of tunneling observable in NVs
4. Analytical tools for fast quantum state preparation in strong-driving regime

THANKS TO: Danish Research Council; Nanophotonics Cluster & Quantum Optics group @*DTU*; Peter Hänggi (Augsburg)

SEE ALSO: `ArXiv:1001.4048`,
Coupling nitrogen vacancy centers in diamond to superconducting flux qubits,
D. Marcos, M. Wubs, J. M. Taylor, R. Aguado, M. D. Lukin, and A. S. Sørensen

shortest pulse: what conditions?

1. $\Delta/\omega \ll 1$: high-frequency limit, RWA
2. $\omega\tau_p \gg 1$: smooth pulse
3. $A/\omega \ll \omega\tau_p$: slowly-varying amplitude
4. $\Phi(\infty) = \Delta\tau_p \int \mathrm{d}x J_1(\frac{A}{\omega}\exp(-x^2)) \leq 1.40\Delta\tau_p$
5. $\Phi(\infty) = 1.40\Delta\tau_p$ for $A/\omega = 2.66$
6. optimal amplitude $A/\omega = 2.66$ gives shortest pulses to invert qubit