Coherent destruction of tunneling in diamond

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1. Intro and abstract

Nitrogen vacancy (NV) centers in diamond are promising candidate qubits for quantum information processing. Recently it has been shown experimentally that their quantum states can be manipulated fast by short and strong light pulses [1]. I proposed that also in the strong-coupling regime and for a smaller interaction between the qubit states, coherent destruction of tunneling (CDT) [2] could be observed, both in pulsed and in continuously driven NV centers [3]. Indeed, for continuous driving, CDT in diamond has recently been observed [4]. NV centers are becoming the work horse for quantum state manipulation in the strong-coupling regime. Besides their efficient interaction with light, NV centers can also be manipulated with magnetic fields. This is the basis for a possible coherent interaction between a collection of NV centers with a flux qubit, forming an interesting hybrid quantum system, where the strong optical transitions of the NVs may enable an interface between superconducting qubits and light [5].

2. Instantaneous CDT

A two-level system with states $\{|0\rangle, |1\rangle\}$ is driven by a pulse, as described by the Hamiltonian

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

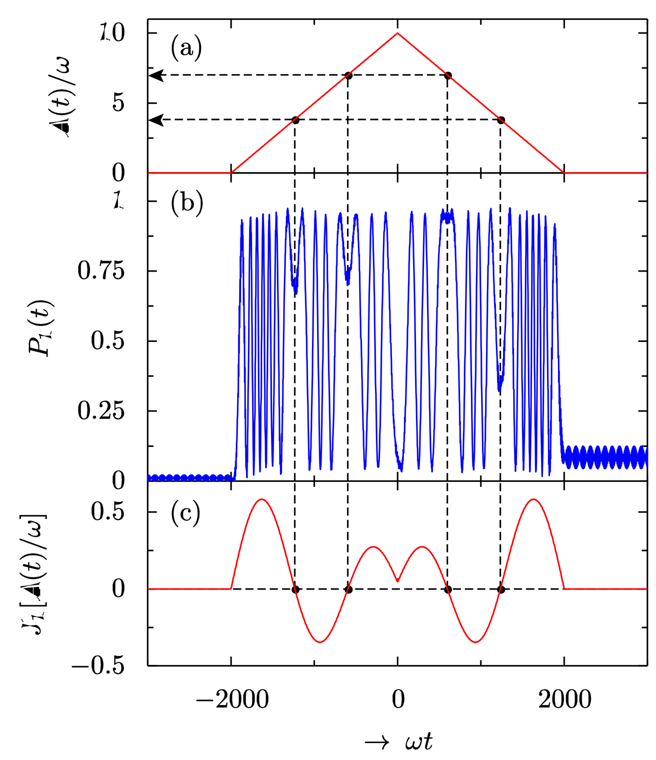
where $V(t) = A(t)\cos(\omega t)$ is the driving field with frequency ω and pulse envelope $A(t)$ of width τ_p.

On resonance $\omega_0 = n_{res}\omega$ and in the regime

$$\omega \gg \Delta, \tau_p^{-1}, \sqrt{A_{max}/\tau_p},$$

the excited-state probability $P_1(t)$ becomes $\sin^2(\Phi(t))$, with the dynamical phase factor

$$\Phi(t) = \Delta \int_{t_0}^{t} d\tau J_{n_{res}}[A(\tau)/\omega)].$$



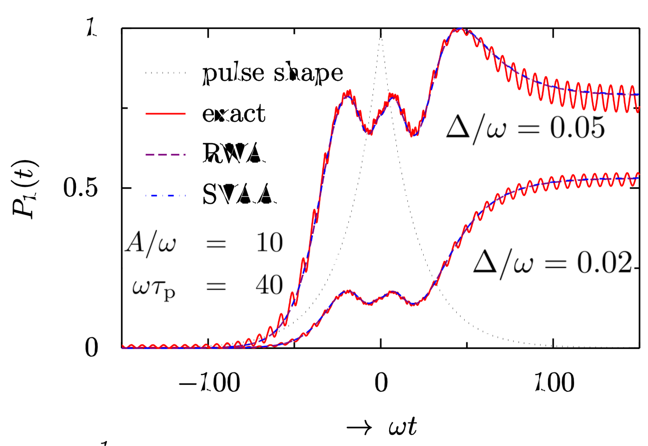
3. Pulse shaping

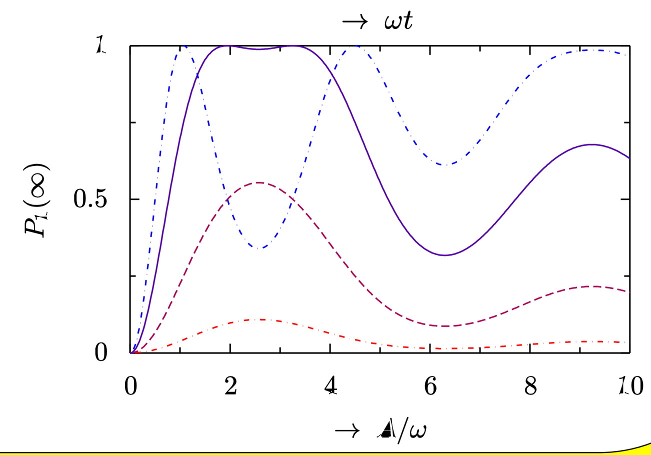
The analytical approximated dynamics enables simple shaping of strong pulses ($A \gtrsim \omega$) to obtain desired final states fast in the CDT regime ($\Delta \ll \omega$).

This leads to fast quantum state manipulation, but not as fast as in Ref. [1], where $\Delta/\omega_0 = \sqrt{2}$ but the dynamics can only be simulated numerically.

If the goal is to invert a qubit fast, then there is no point in making $A \gg \omega$. Shown final-state populations $P_1(t = \infty)$ are $\omega\tau_p$ = 20, 50, 100, and 150, from bottom to top.

The detailed shape of the smooth pulse is irrelevant for $P_1(t = \infty)$, only the $\Phi(\infty)$ counts. Becomes pulse-area law for $\omega = \omega_0$ in the limit of weak driving ($A \ll \omega$).





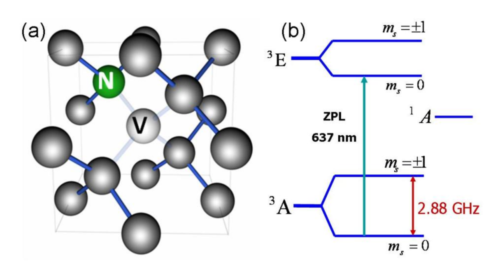
4. Proposed realization in diamond

Nitrogen-vacancy centers in diamond: Qubits at room temperature. Coherence time milliseconds, manipulated in nanoseconds [1]. Qubit is two levels of S=1 ground state. Hamiltonian:

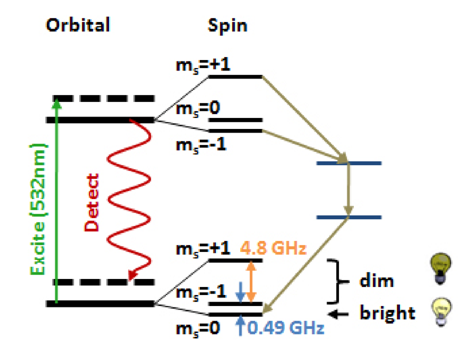
$$H_0 = \Delta S_z^2 + g_e\mu_B \mathbf{B}\cdot\mathbf{S}, \qquad V(t) = A(t)\cos(\omega t)\mathbf{n}_d \cdot \mathbf{S}.$$

N-V axis is anisotropy axis. State initialization and readout optically via excited state.

Two proposed realizations of CDT Hamiltonian:
I. Drive slightly off-axis
II. On-axis (diagonal) driving, add static transverse B field. Stronger driving needed than in Ref. [1] to flip qubit (see [3]).

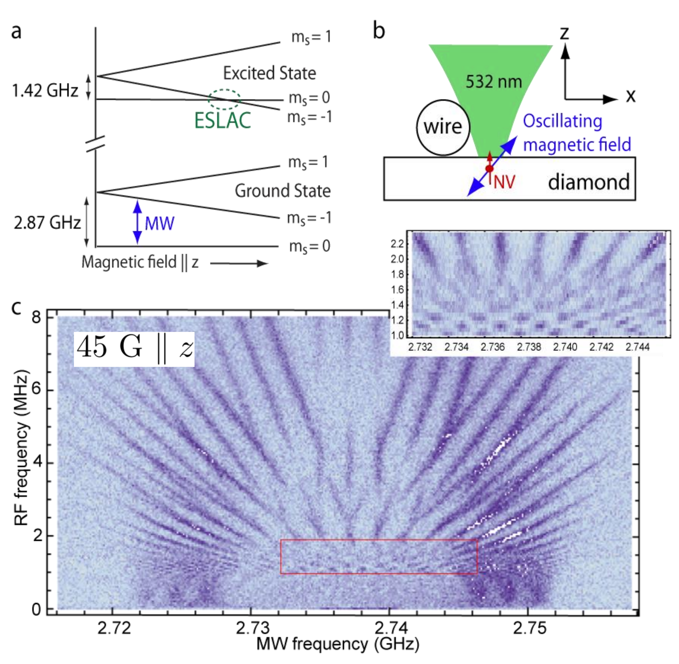


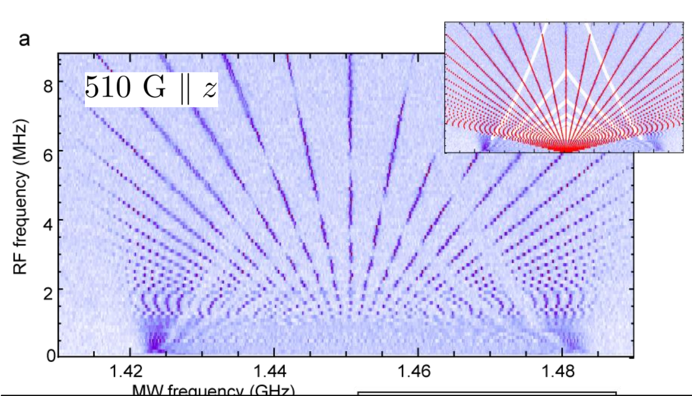
picture: Wrachtrup group

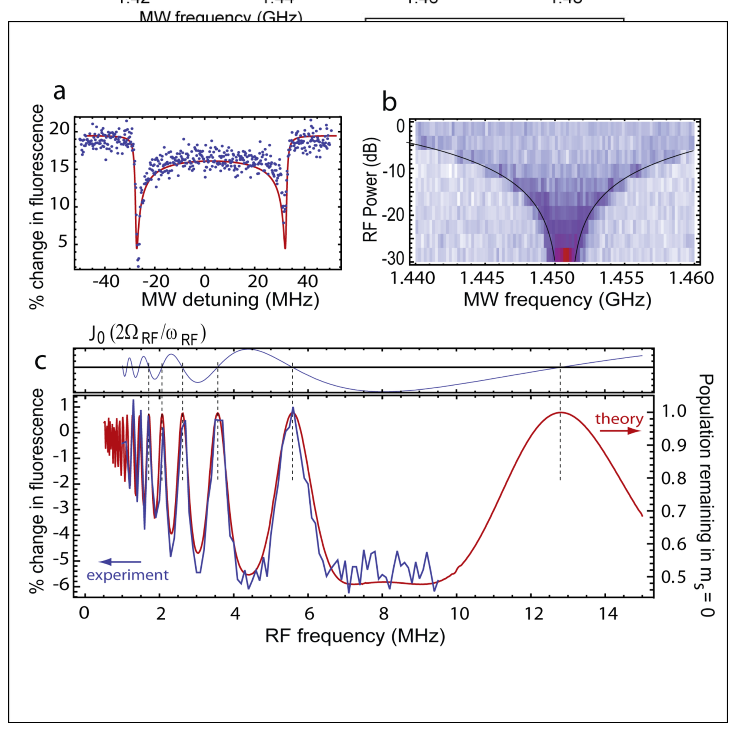


picture: Ref. [1]

5. CDT seen in diamond (Ref. [4])







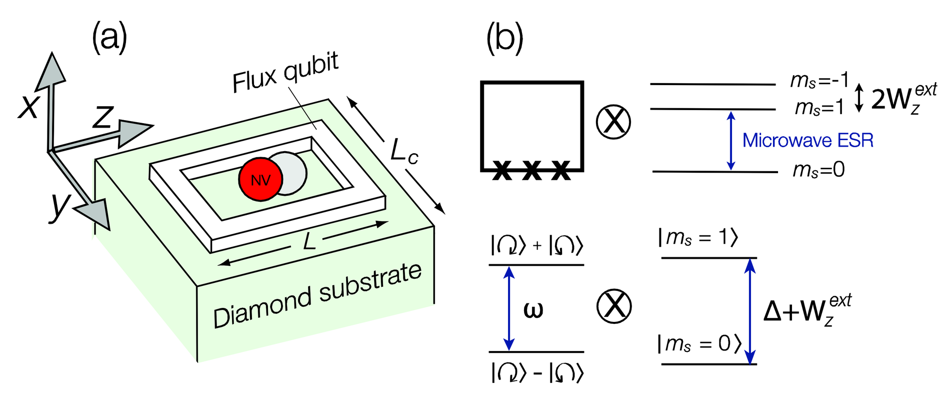
Experiments by Childress and McIntyre [4]: Simultaneous excitation by weak MWs to drive electronic spin transitions and strong radio-frequency excitation to drive nuclear spin resonance:

$$H = \frac{\Delta}{2}\sigma_z + \Omega_{MW}\cos(\omega_{MW}t)\sigma_x + \Omega_{rf}\cos(\omega_{rf}t)\sigma_z$$

Quantum state readout by fluorescence (darker is lower fluorescence). Higher B field polarizes ^{14}N nuclear spins.

Resonant MW excitation ($\omega_{MW} \simeq \Delta$) versus rf frequency, illustrating CDT.

6. Coupling NV centers in diamond to superconducting flux qubits (Ref. [5])



A new hybrid qubit is proposed, a flux qubit coupled to an ensemble of NV centers in diamond.

Energies of FQ and NV both a few GHz.

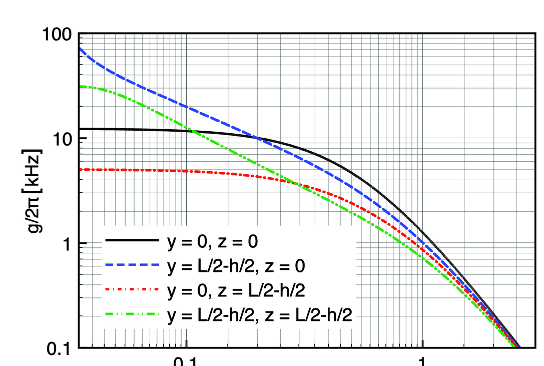
NV feels different B fields for clockwise and anti-clockwise flux qubit states, which defines a coupling.

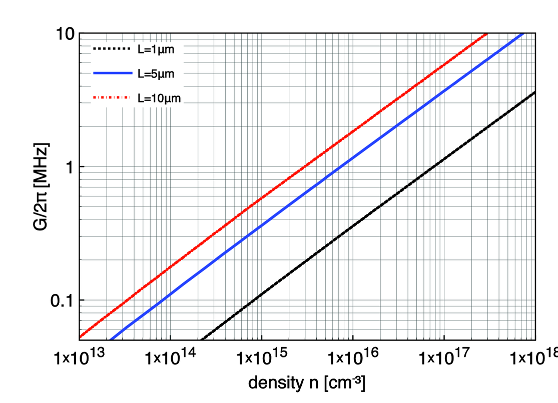
Coupling to a single NV $g = (2\pi) \times 12$kHz, not strong enough to beat decoherence.

Coupling to an ensemble of NVs, $\sqrt{N}$ enhancement. $G \simeq 1$MHz for $n > 10^{16}\text{cm}^{-3}$ enables coherent interaction.

Paramagnetic impurities cause decoherence.

Nuclear spins are advantage: map electronic states onto them





7.Conclusions and outlook

- Instantaneous CDT: possible for strong pulses
- State preparation by pulse shaping in strong-coupling regime
- Proposed to realize in NV centers in diamond
- CDT recently already observed in diamond
- Flux qubit pus NVs in diamond make promising hybrid system
- Quantum state manipulation in strong-coupling regime has the future [6]

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