Longitudinal coupling between electrically driven spin-qubits and a resonator

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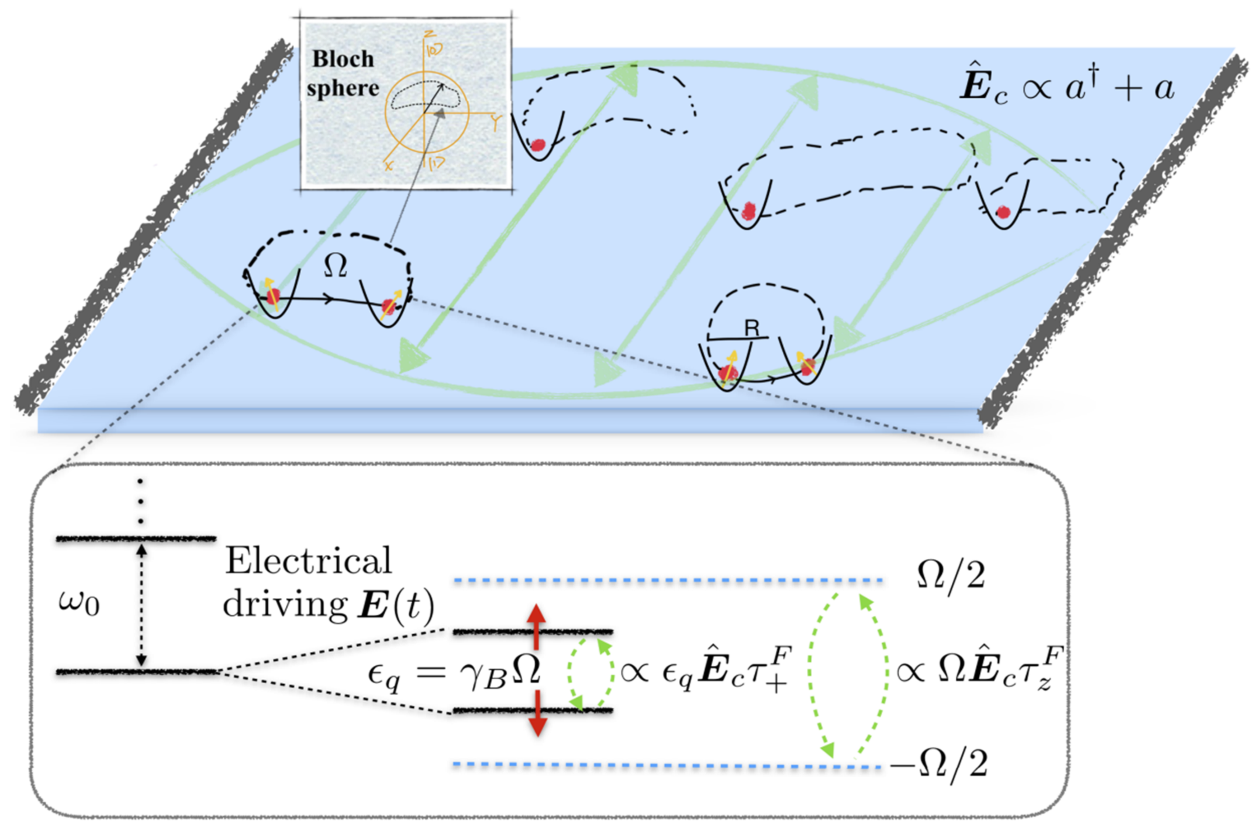
Motivation

- Electron/hole-spin qubits $\rightarrow$ long coherence times and scalability
- Electric field $+$ Spin orbit interaction $\rightarrow$ Access spin states [1]
- Floquet qubits more robust against noise than their static counterparts [2]
- Experiment shows that shuttling electron spins enhances their coherence [3]

System and model Hamiltonian



Periodic driving $\rightarrow$ Berry-phase $\gamma_B \leftrightarrow$ quasi-energy splitting

$$H_{\rm tot}(t) = \underbrace{\frac{\boldsymbol{p}^2}{2m} + U(\boldsymbol{r}) + e\boldsymbol{r}\cdot\boldsymbol{E}(t) + H_{SO}}_{H_{el}(t)} + \underbrace{e\boldsymbol{r}\cdot\boldsymbol{E}_c(a^\dagger + a)}_{H_{e-p}} + \omega_c a^\dagger a\,,$$

$H_{SO} = \alpha(p_x\sigma_y - p_y\sigma_x)$, and $\boldsymbol{E}(t+T) = \boldsymbol{E}(t)$

Floquet spin-qubit states

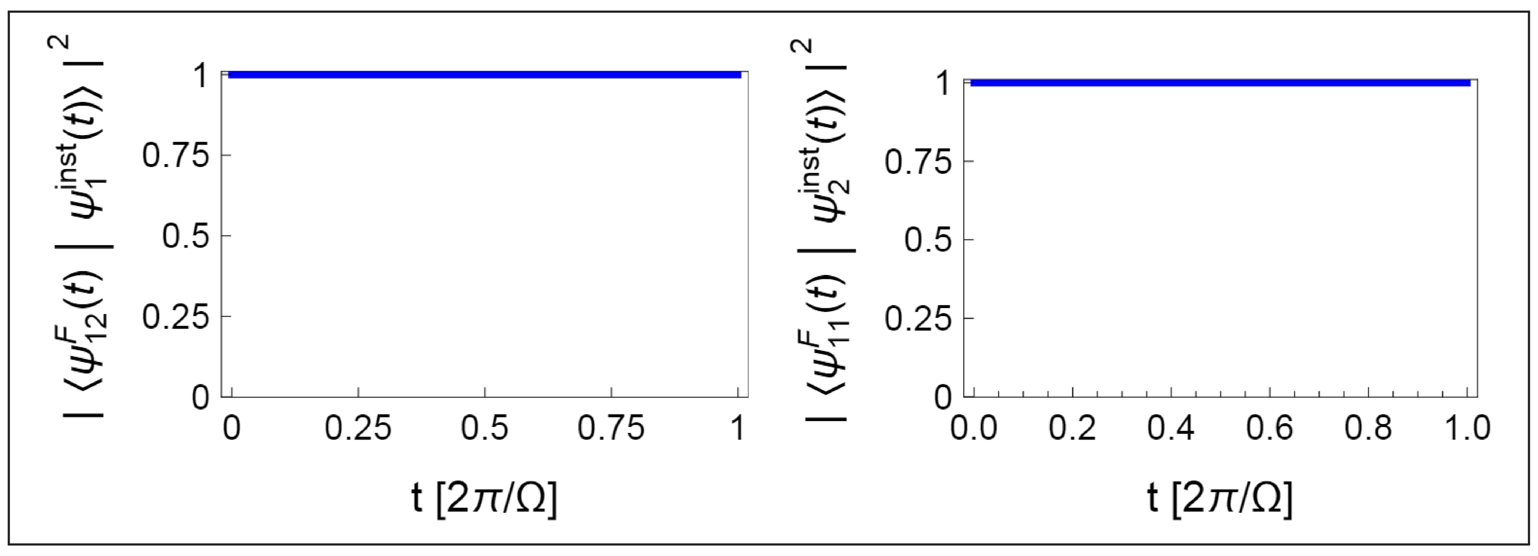
- If $H_{el}(t+T) = H_{el}(t)$, with $T = 2\pi/\Omega$, solutions to Schrödinger equation $i\partial_t|\Psi(t)\rangle = H_{el}(t)|\Psi(t)\rangle$ are *Floquet states* $|\Psi_j(t)\rangle$ written as,

$$|\Psi_j(t)\rangle = e^{-i\epsilon_j t}|\psi_j(t)\rangle\,,\; j = 0,1,2...,$$

where the *periodic Floquet mode* $|\psi_j(t)\rangle$ obey:

$$(H_{el}(t) - i\partial_t)|\psi_j(t)\rangle = \epsilon_j\,|\psi_j(t)\rangle\,,\;\; |\psi_j(t+T)\rangle = |\psi_j(t)\rangle\,.$$

- **Qubit states** $\{|\Psi^F_{\tilde{q}}(t)\rangle\}_{\tilde{q}=0,1}$: Floquet states with most overlap with the lowest two instantaneous ground states of $H_{el}(t)\,|\Psi^{\rm inst}_q(t)\rangle = \epsilon^{\rm inst}_q(t)\,|\Psi^{\rm inst}_q(t)\rangle$



Assuming a driven harmonic potential in adiabatic regime with parameters $E_0 = 0.1$, $\Omega = 0.3$ and $\omega_0 = 1$, here we show the plots of $|\langle\Psi^F_i(t)|\Psi^{\rm inst}_{1(2)}(t)\rangle|^2$ with instantaneous states $|\Psi^{\rm inst}_{1(2)}(t)\rangle$ and the Floquet states that had the most overlap to choose $\{|\Psi^F_i(t)\rangle\}_{i=11,12}$ as the qubit states.

Hamiltonian in the Floquet qubit subspace

$$H_{s-p}(t) = [g_z(t)\tau^F_z + (g_+(t)\tau^F_+ + {\rm h.c.})](a^\dagger + a) + \omega_c a^\dagger a\,,$$

$$g_z(t) = \frac{\boldsymbol{R}_c}{2}\cdot\frac{d}{dt}\left[\langle\psi_1(t)|\boldsymbol{m}|\psi_1(t)\rangle - \langle\psi_0(t)|\boldsymbol{m}|\psi_0(t)\rangle\right],$$

$$g_+(t) = ie^{i\epsilon_q t}\boldsymbol{R}_c\cdot\left(\epsilon_q - i\frac{d}{dt}\right)\langle\psi_1(t)|\boldsymbol{m}|\psi_0(t)\rangle,\;\; \boldsymbol{m} = [\sigma_x \;\; -\sigma_y]^T$$

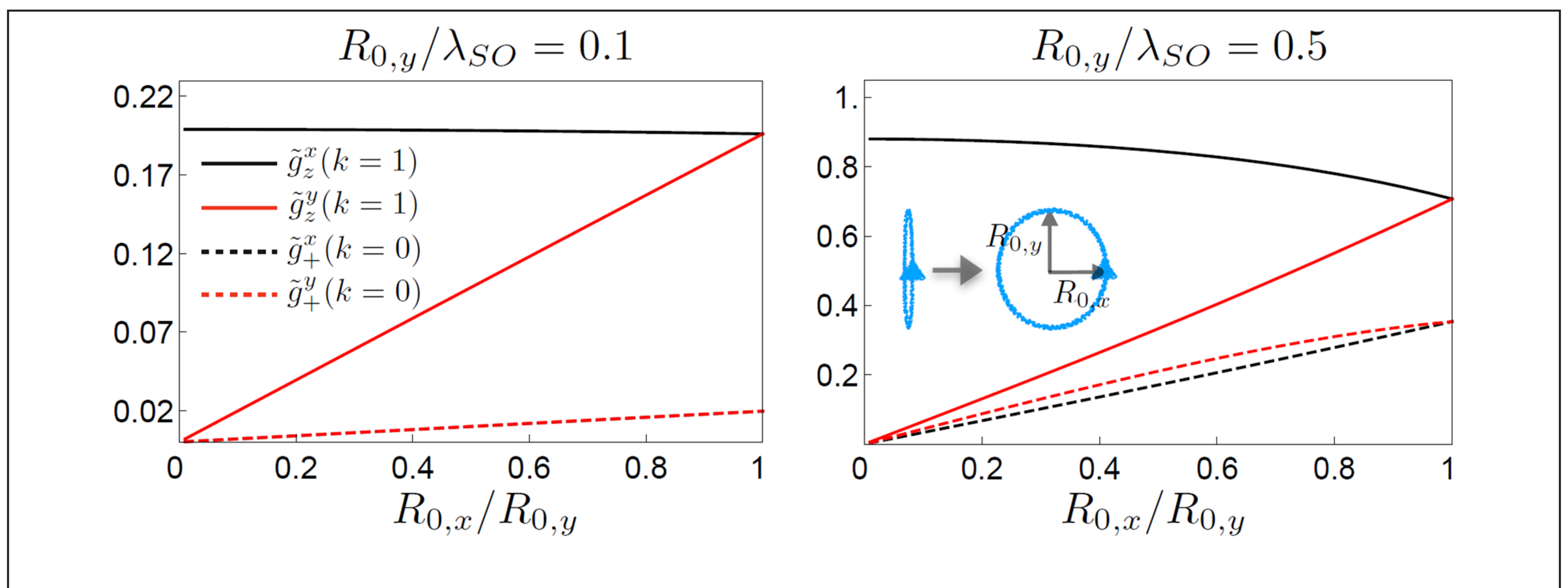
- Longitudinal term $g_z(t) \rightarrow 0$ in static case

Longitudinal readout

- The readout of the Floquet spin-qubit can be achieved faster [4] by utilizing longitudinal spin-photon couplings instead of transverse interactions due to better pointer separation at initial times as,

$$\langle a(t)\rangle = -i\,(g_z(k=1)/\kappa)\,\langle\tau^F_z\rangle(1 - e^{-\kappa t/2})$$

Dependence of the coupling on the QD trajectory



Coupling strength as path is varied from a line to a circle. For Ge/SiGe hole-spin $g_z/2\pi \approx 10$ MHz and $g_z/2\pi \approx 4$ MHz for GaAs electron spin

Decoherence

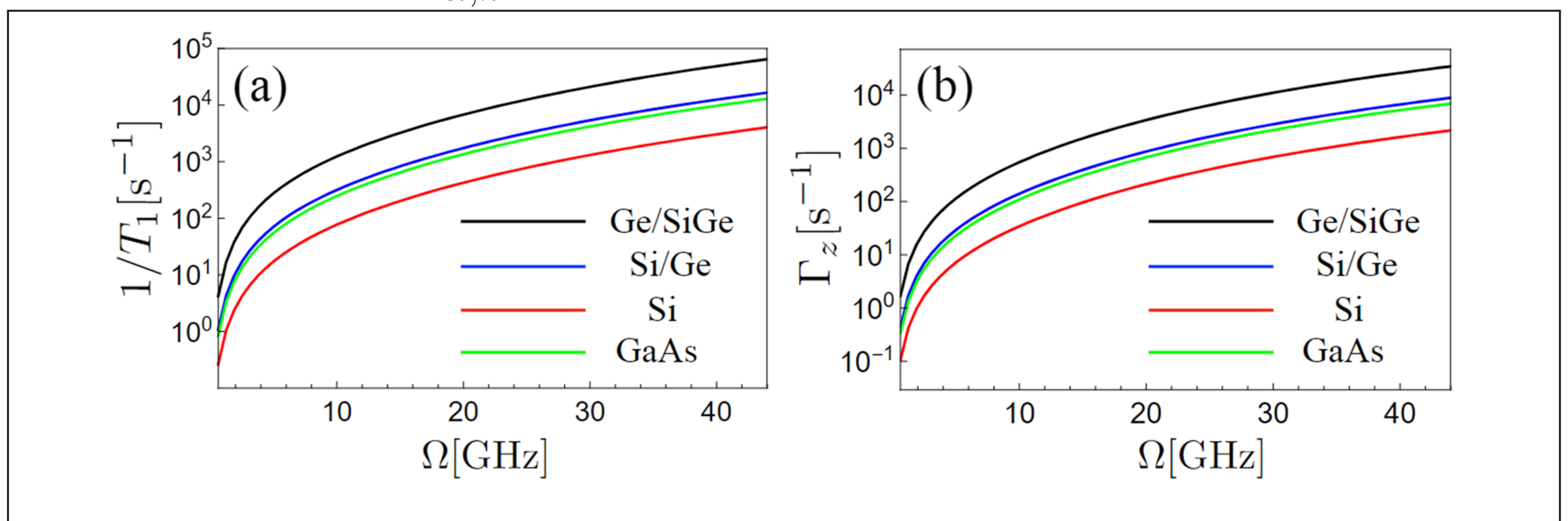
- Following a Floquet-Born-Markov approach, the rate equation for the Floquet spin-qubit in the interaction picture is

$$\dot{\rho}_S(t) = \sum_{s=\pm,z}\Gamma_s\mathcal{D}_s[\rho_S(t)]\,,$$

$$\mathcal{D}_s[\rho_S(t)] = \tau^F_s\rho_S(t)(\tau^F_s)^\dagger - \frac{1}{2}\{(\tau^F_s)^\dagger\tau^F_s, \rho_S(t)\}\,,$$

$$\Gamma_\pm = \left(\frac{\Omega\lambda_0}{\omega_0\lambda_{SO}}\right)^2\sum_{\alpha,k}|m_{\pm,\alpha}(k)|^2(k\pm\gamma_B)^2 J_\alpha[\Omega(k\pm\gamma_B)]$$

$$\Gamma_z = \left(\frac{\Omega\lambda_0}{\omega_0\lambda_{SO}}\right)^2\sum_{\alpha,k}|m_{z,\alpha}(k)|^2k^2J_\alpha(k\Omega),$$ $J_\alpha(\omega)$: bath spectral function



(a) *Relaxation* $1/T_1 = \Gamma_+ + \Gamma_-$ *and* (b) *dephasing* $1/T_2 = \Gamma_z$ *rates for hole-based (black, blue, red) and electron-based Floquet spin-qubits (green)*

- **Qubit power dissipation:** $P \approx \Gamma_+\Omega$

Two qubit CPHASE gate

- For two Floquet spin-qubits, with $\Delta = \omega_c - \Omega$, we obtained:

$$H_{2q} = \Delta a^\dagger a + (g_{z,1}\tau^F_{z,1} + g_{z,1}\tau^F_{z,2})(a^\dagger + a),$$

known to realise a CPHASE gate [5] for a gate time $t_g = \pi\Delta/(8g_{z,1}g_{z,2})$. For Ge/SiGe hole-spin $t_g \approx 50$ ns and for GaAs electron spin $t_g \approx 100$ ns, show that $t_g \ll T_1 \sim 0.1$ms

Geometric origin of the interaction

- For general $U(\boldsymbol{r})$, the geometric nature of the interaction is revealed in instantaneous frame defined by the unitary $\mathcal{U} \equiv \mathcal{U}[\boldsymbol{E}(t)]$,

$$H_{s-p} = E_{c,\beta}\dot{E}_\alpha\left(m^z_{\alpha\beta}\tau^F_z + m^+_{\alpha\beta}e^{i\epsilon_q t}\tau^F_+ + {\rm h.c.}\right)(a^\dagger + a),$$

where $m^z_{\alpha\beta}(t),\, m^+_{\alpha\beta}(t) \propto \mathcal{F}^E_{\alpha\beta}$ where, $\mathcal{F}^E_{\alpha\beta} = \partial_\alpha\mathcal{A}^E_\beta - \partial_\beta\mathcal{A}^E_\alpha + i[\mathcal{A}^E_\alpha, \mathcal{A}^E_\beta]$ is the Berry curvature and $\mathcal{A}^E_\alpha = i\mathcal{U}^\dagger\partial_{E_\alpha}\mathcal{U}$ is the Berry connection

Conclusion & Outlook

- Defined Floquet spin-qubit, unraveled tunable transverse and longitudinal spin-photon coupling to a resonator, constructed a CPHASE two-qubit gate, and estimated the coherence in the presence of ohmic noise
- Revealed the geometric nature of interaction using adiabatic perturbation theory
- Future: Generalise to multiple qubits and evaluate the phonon-induced decoherence

References

[1] Golovach et al., PRA **81**, 022315 (2010)
[2] Huang et al., PRA **15**, 034065 (2021)
[3] Mortemousque et al., PRXQ **2**, 030331 (2021)
[4] Didier et al., PRL **115**, 20360 (2015)
[5] Harvey et al., PRB **97**, 235409 (2018)

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