Floquet spin qubits in gate-defined quantum dots coupled to a microwave cavity

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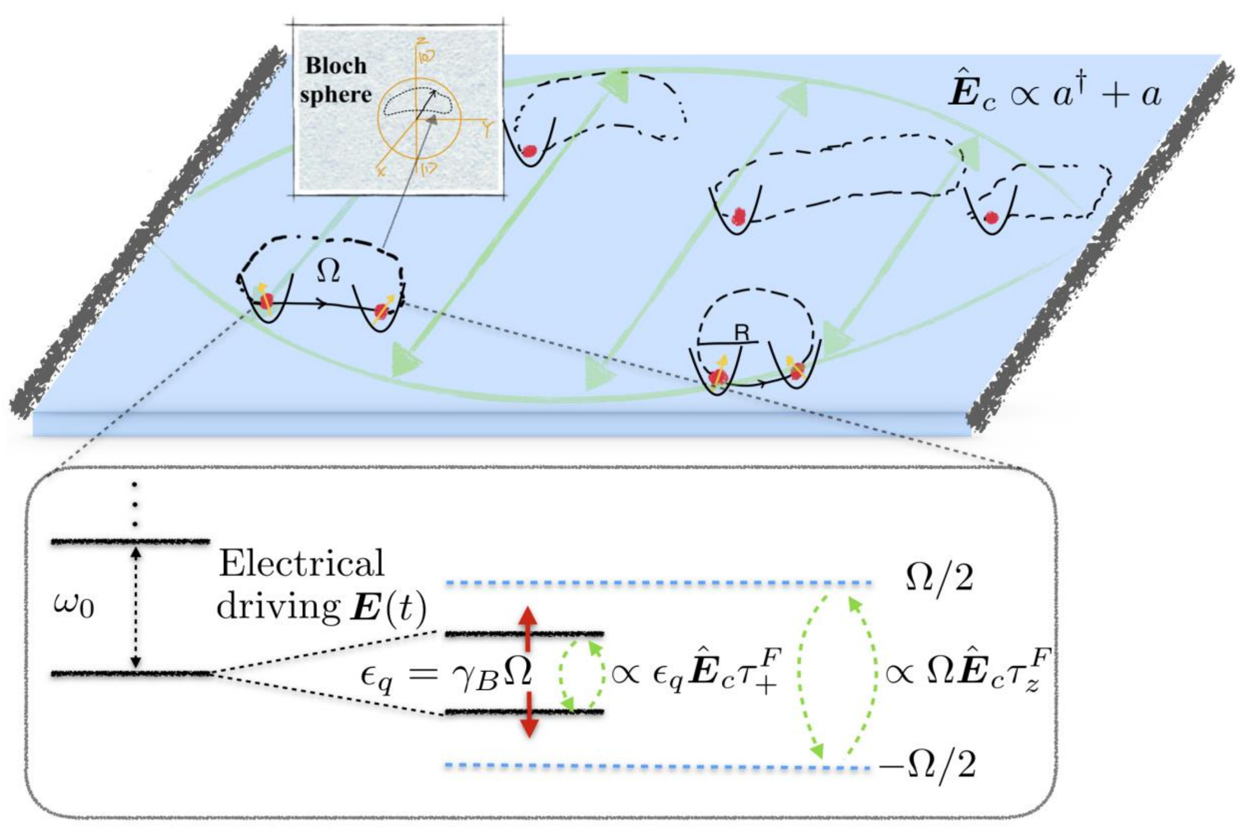
Email: sarathprem@magtop.ifpan.edu.pl, **arXiv:2301.10163 (Longitudinal coupling between Floquet spin qubits and a microwave resonator)**

Abstract: Most semi-conducting qubits require external magnetic fields to define the spin qubit, which can activate various charge noise mechanisms. Here we study spin qubits confined in quantum dots at zero magnetic fields, that are driven periodically by electrical fields and are coupled to a microwave resonator. Using Floquet theory, we identify a well-defined Floquet spin-qubit originating from the lowest degenerate spin states in the absence of driving. We find both transverse and longitudinal couplings between the Floquet spin qubit and the resonator, which can be selectively activated by modifying the driving frequency and show how these couplings can facilitate fast qubit readout and the implementation of a two-qubit CPHASE gate. Finally, we use adiabatic perturbation theory to demonstrate that the spin-photon couplings originate from the non-Abelian geometry of states endowed by the spin-orbit interactions, rendering these findings general and applicable to a wide range of solid-state spin qubits.

Motivation

- Electron/hole-spin qubits → long coherence and scalability
- Electric field on charge + Spin orbit interaction →Access spin states [Golovach et al., PRA **81**, 022315 (2010)]
- Spin-photon coupling → long-range interaction + entanglement → favorable for scalability
- Floquet qubits offer protection against noise [Huang et al., PRA **15**, 034065, (2021)]
- Experiment show shuttling electron enhances its coherence time due to motional narrowing [Mortemousque et al., PRXQ **2**, 030331, (2021)]

System and model Hamiltonian



$$H_{tot}(t) = H_0(t) + H_{SO} + H_{e-p} + \omega_c a^\dagger a,$$
$$H_0(t) = \frac{\boldsymbol{p}^2}{2m} + U(\boldsymbol{r}) + \frac{1}{2} g\mu_B B\, \sigma_z + e\, \boldsymbol{r}\cdot \boldsymbol{E}(t),$$
$$H_{SO} = \alpha(p_x\sigma_y - p_y\sigma_x) + \beta(-p_x\sigma_x + p_y\sigma_y)$$
$$H_{e-p} = e\, \boldsymbol{r}\cdot \boldsymbol{E}_c(a^\dagger + a).$$

Floquet qubit

If $H(t+T) = H(t) \rightarrow$ *Floquet states* $|\Psi(t)\rangle$ satisfy:

$$i\partial_t|\Psi(t)\rangle = H(t)|\Psi(t)\rangle \rightarrow |\Psi_j(t)\rangle = e^{-i\epsilon_j t}|\psi_j(t)\rangle;$$
$$|\psi_j(t+T)\rangle = |\psi_j(t)\rangle$$

ϵ_j: Quasi-energy defined Mod$[2\pi/T]$, and time-independent.

After an evolution over period T, $\epsilon_j = \bar{\epsilon}_j - \phi_{G,j}/T$

$$\bar{\epsilon}_j = \frac{1}{T}\int_0^T dt\, \langle\psi_j(t)|H_{el}(t)|\psi_j(t)\rangle, \qquad \phi_{G,i} = i\int_0^T dt\, \langle\psi_j(t)|\partial_t|\psi_j(t)\rangle$$

where $\bar{\epsilon}_j$ is the average energy over T and $\phi_{G,i}$ is the geometrical phase.

- Adiabatic case: $\phi_{G,i}(T\rightarrow\infty) = \gamma_{B,i}$, becomes Berry phase, causes splitting: $\epsilon_1 - \epsilon_0 = \frac{\Omega}{2\pi}(\gamma_{B,0} - \gamma_{B,1})$ in the lowest degenerate doublet
- (Floquet) Qubit encoded in Floquet states

Static case $\boldsymbol{E}(t) = 0$

In lowest energy subspace, electron-spin interaction:

$$H_{s-p} = i\,\epsilon_q \frac{\boldsymbol{R}_c}{\lambda_{SO}}\cdot(\boldsymbol{m}_+\tau_+ - \boldsymbol{m}_-\tau_-)(a^\dagger + a)$$

where $\boldsymbol{m}_+ = \langle\psi_0|\lambda_{SO}\,\boldsymbol{\lambda}_{SO}{}^{-1}\boldsymbol{\sigma}|\,\psi_1\rangle, \boldsymbol{R}_c = e\frac{E_c}{m}\omega_0^2.$

- Transverse coupling slower→ longer time for pointer state separation

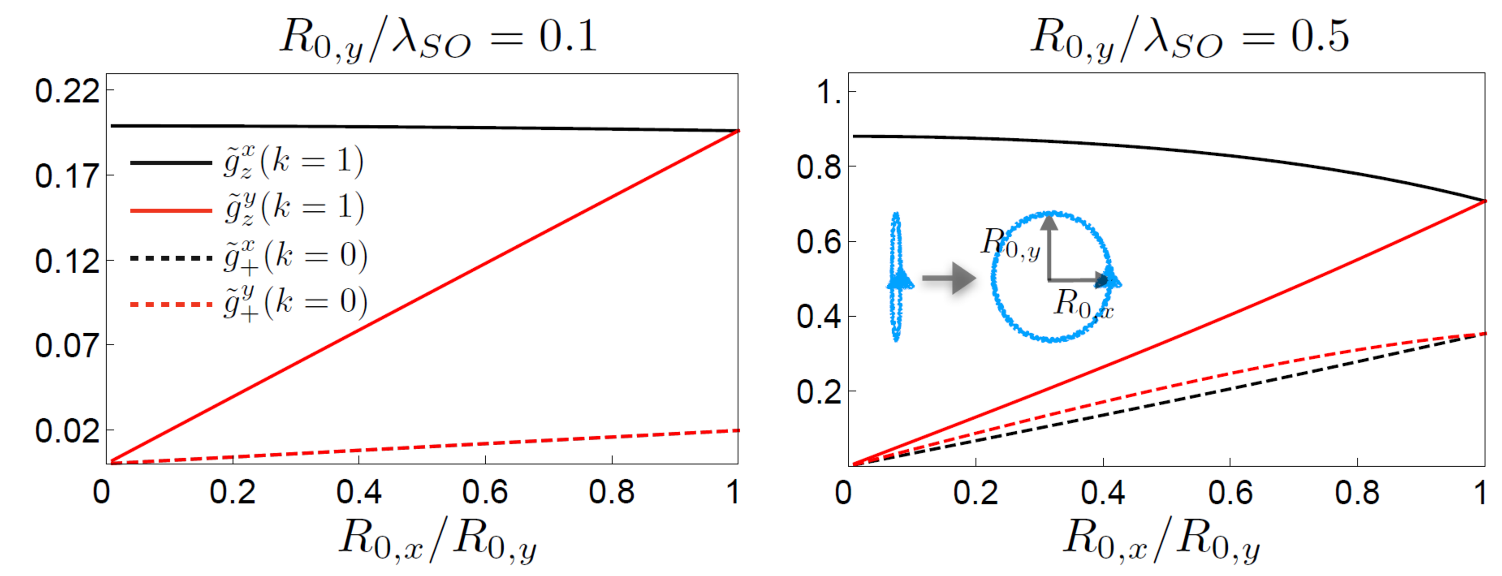
Effective Hamiltonian in driven case & $B = 0$

Projected to lowest two level subspace, electron-spin interaction is:

$$H_{s-p}(t) = [g_z(t)\tau_z^F + (g_+(t)\tau_+^F + g_-(t)\tau_-^F)](a^\dagger + a)$$
$$g_z(t) = \frac{\boldsymbol{R}_c}{2\,\lambda_{SO}}\cdot\frac{d}{dt}\boldsymbol{m}_z(t), \qquad g_+(t) = i\,e^{i\,\epsilon_q t}\frac{\boldsymbol{R}_c}{\lambda_{SO}}\cdot\left(\epsilon_q - i\frac{d}{dt}\right)\boldsymbol{m}_+(t)$$

where, $\boldsymbol{m}_z(t) = \langle\psi_1|\boldsymbol{m}(t)|\,\psi_1\rangle - \langle\psi_0|\boldsymbol{m}(t)|\,\psi_0\rangle, \boldsymbol{m}_+(t) = \langle\psi_1|\boldsymbol{m}(t)|\,\psi_0\rangle$, $|\psi_i\rangle$ are the two Floquet states in the lowest energy subspace and ϵ_q is the qubit splitting in the lowest subspace.

- Longitudinal coupling $g_z(t) \propto k\, e^{i\,k\,\Omega t}$ is unique to the dynamic case



CPHASE gate, read out, decoherence & geometric nature

- In absence of magnetic field, CPHASE gate between two qubits in same cavity with the evolution [Harvey et al., PRB **97**, 235409 (2018)] of

$$H_{2q} = (\omega_c - \Omega)a^\dagger a + [g_{z,1}(k=1)\tau_{z,1}^F + g_{z,2}(k=1)\tau_{z,2}^F](a^\dagger + a),$$

$$U(t) = e^{i\,(\omega_c-\Omega)a^\dagger a}D[\alpha(t)]e^{iJ(t)\tau_{z,1}^F\tau_{z,2}^F},$$

for a time $t_g = \frac{\pi}{4}\frac{(\omega_c-\Omega)}{(2g_{z,1}g_{z,2})} \propto T$ & $J(t) = \frac{2g_{z,1}g_{z,2}}{(\omega_c-\Omega)^2}[(\omega_c-\Omega)t - \sin((\omega_c-\Omega)t)].$

- $\omega_c \approx \Omega$ →Faster read out via Longitudinal coupling as proved in [Didier et al., PRL **115 (20)**, 20360, (2015)]

- Decoherence due to charge fluctuations: $\dot{\rho}(t) = \sum_{s=\pm,z}\Gamma_s\mathcal{D}_s[\rho(t)]$,

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

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

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

- Adiabatic perturbation → spin-photon coupling originates from the non-Abelian geometry of states endowed by the spin-orbit interactions:

$$H_{s-p}(t) = \frac{\dot{R}_\alpha}{\lambda_{SO}}\left(\mathcal{A}_\alpha - \frac{R_{c,\beta}}{\lambda_{SO}}\mathcal{F}_{\alpha\beta}(a^\dagger + a)\right) + \omega_c a^\dagger a$$

where $\mathcal{A}_\alpha = \mathcal{P}_0 p_\alpha \mathcal{P}_0 = m_\alpha$, $\mathcal{F}_{\alpha\beta} = i[\mathcal{A}_\alpha, \mathcal{A}_\beta] = \frac{2\sigma_z\epsilon_{\alpha\beta z}}{\lambda_{SO}^2}$ are non-Abelian Berry connections and curvature respectively.

Conclusion & Outlook

- Obtained effective Hamiltonian for qubit subspace and longitudinal read out
- Geometric nature of interaction revealed with Adiabatic perturbation
- Future: Generalize to multiple quantum dots as they do not interact with each other and explore the decoherence effects due to phonons

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