Spin and charge dynamics in carbon nanotube circuits probed by transport and cQED

T. Kontos
LPA, ENS Paris

Co-workers:
Th: A. Cottet, B. Douçot

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Emergence of model systems for condensed matter

SWNT in a conventional transport experiment

- Experimental study of artificial atoms, molecules or wires
- Natural probe of electronic systems = transport
- Single Wall Nanotubes (and nanowires) as building block

Model systems for 1D to 0D electrons: coherent manipulation of the quantum state of electrical circuits or strongly correlated electronic systems
Combining nanotubes with electrodes of very different nature

Depending on nature/regime/geometry of contacts, different fundamental physics can be probed.

Non-local orbitally coherent spin valve

Artificial magnetic impurity

Cooper pair splitter

How to go beyond such transport experiments?
Hybrid circuit Quantum Electro-Dynamics

From cavity QED ... To circuit QED ... ... To hybrid cQED with quantum dots

A. Blais et al., PRA (2004)
M.R. Delbecq et al. PRL (2011)
T. Frey et al. PRL (2012)

→ Light-matter interaction @ the most elementary level
→ Spin-photon coupling
→ Probe/Manipulate micro- or macroscopic quantum states
→ Take advantage of the versatility of quantum dots (many-body physics... )
I. Out of equilibrium charge dynamics in a cQED architecture
II. Mesoscopic conductors in a cQED architecture
III. Non-collinear magnetoelectronics with a quantum dot
I. Out of equilibrium charge dynamics in a cQED architecture

II. Mesoscopic conductors in a cQED architecture

III. Non-collinear magnetoelectronics with a quantum dot
Coupling to single quantum dot circuits

M.R. Delbecq et al. PRL (2011)

Coupling to open quantum systems

Photon mediated polaronic interaction between distant quantum dots

Need to use double quantum dots for manipulating quantum information
Our circuit QED architecture
SWNT Double quantum dots for hybrid cQED

J.J. Viennot et al. (arXiv:1310.4363)
Coupling mechanism of a Double QD

Asymmetric coupling particularly interesting (address intra-dot transitions)
Coupling mechanism of a Double QD

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Coupling mechanism of a Double QD

What is the cavity detector exactly sensitive to?

Asymmetric coupling particularly interesting (address intra-dot transitions)

What is the cavity detector exactly sensitive to?
Towards CNT-based quantum information devices

- Preserve coherence (closed QD)
- Bring system to resonance with cavity

« Strong » confinement in SWNT

\[ \Gamma_{\text{lead}} \approx 0.1 - 1 \text{GHz} \]

Cavity mode couples to detuning of DQD

J.J. Viennot et al. (arXiv:1310.4363)
See also, in SC Nanowires and 2DEG:
T. Frey et al. PRL (2012)
Toida et al. PRL (2013)
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Cavity mode couples to detuning of DQD

- Can we be quantitative?

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Toida et al. PRL (2013)
Driving the effective spin out of equilibrium

System hamiltonian:

\[ \hbar \Omega = \sqrt{(2t)^2 + (\epsilon_L - \epsilon_R)^2}, \quad g = g_0 \sin \theta, \quad \theta = \arctan \frac{2t}{\epsilon_L - \epsilon_R}, \]

\[ H = \frac{\hbar \Omega}{2} \sigma_z + E_0 \sigma_0 + E_2 \sigma_2 + \hbar \omega_0 a^\dagger a + \hbar g (\sigma_- a^\dagger + \sigma_+ a) + \hbar \epsilon_{in} (e^{-i \omega_{dt} a^\dagger} + e^{i \omega_{dt} a}) + H_{Bath} \]

J.J. Viennot et al. (arXiv:1310.4363)
Driving the effective spin out of equilibrium

\[ \Delta = \Omega - \omega_d \text{ and } \delta = \omega_0 - \omega_d \]

Effective spin-drive and cavity-drive detuning

\[
\frac{d\langle a \rangle}{dt} = -(\kappa/2 + i\delta)\langle a \rangle - i\epsilon_{in} - ig\langle \sigma_- \rangle \\
\frac{d\langle \sigma_- \rangle}{dt} = -(\gamma/2 + \Gamma_\phi + i\Delta)\langle \sigma_- \rangle + ig\langle a(\sigma_p - \sigma_m) \rangle \\
\frac{d\langle \sigma_p \rangle}{dt} = -ig(\langle a\sigma_+ \rangle - \langle a^\dagger\sigma_- \rangle) + \sum_{i \neq p} \Gamma_{pi}\langle \sigma_i \rangle - \sum_{i \neq p} \Gamma_{ip}\langle \sigma_p \rangle \\
\frac{d\langle \sigma_m \rangle}{dt} = ig(\langle a\sigma_+ \rangle - \langle a^\dagger\sigma_- \rangle) + \sum_{i \neq m} \Gamma_{mi}\langle \sigma_i \rangle - \sum_{i \neq m} \Gamma_{im}\langle \sigma_m \rangle \\
\frac{d\langle \sigma_j \rangle}{dt} = \sum_{i \neq j} \Gamma_{ji}\langle \sigma_i \rangle - \sum_{i \neq j} \Gamma_{ij}\langle \sigma_j \rangle
\]

- Coupled electron photon equation of motion (optical Bloch-Redfield type equation)
- Effective spin -> \( \sigma_z = \sigma_p - \sigma_m \) if double dot occupied by one excess charge

J.J. Viennot et al. (arXiv:1310.4363)
Driving the effective spin out of equilibrium

\[ \Delta = \Omega - \omega_d \text{ and } \delta = \omega_0 - \omega_d \]

\[
\frac{d\langle a \rangle}{dt} = -(\kappa/2 + i\delta)\langle a \rangle - i\epsilon_{in} - ig\langle \sigma_- \rangle \\
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J.J. Viennot et al. (arXiv:1310.4363)
Driving the effective spin out of equilibrium

\[ \Delta = \Omega - \omega_d \quad \text{and} \quad \delta = \omega_0 - \omega_d \]

**Cavity drive**

\[
\frac{d\langle a \rangle}{dt} = -(\kappa/2 + i\delta)\langle a \rangle - i\epsilon_{in} - ig\langle \sigma_- \rangle
\]

\[
\frac{d\langle \sigma_- \rangle}{dt} = -(\gamma/2 + \Gamma_\phi + i\Delta)\langle \sigma_- \rangle + ig\langle a(\sigma_p - \sigma_m) \rangle
\]

\[
\frac{d\langle \sigma_p \rangle}{dt} = -ig(\langle a\sigma_+ \rangle - \langle a^\dagger\sigma_- \rangle) + \sum_{i \neq p} \Gamma_{pi}\langle \sigma_i \rangle - \sum_{i \neq p} \Gamma_{ip}\langle \sigma_p \rangle
\]

**Photon drive**

\[
\frac{d\langle \sigma_m \rangle}{dt} = ig(\langle a\sigma_+ \rangle - \langle a^\dagger\sigma_- \rangle) + \sum_{i \neq m} \Gamma_{mi}\langle \sigma_i \rangle - \sum_{i \neq m} \Gamma_{im}\langle \sigma_m \rangle
\]

\[
\frac{d\langle \sigma_j \rangle}{dt} = \sum_{i \neq j} \Gamma_{ji}\langle \sigma_i \rangle - \sum_{i \neq j} \Gamma_{ij}\langle \sigma_j \rangle
\]

J.J. Viennot et al. (arXiv:1310.4363)
Driving the effective spin out of equilibrium

\[ \Delta = \Omega - \omega_d \text{ and } \delta = \omega_0 - \omega_d \]

\[
\begin{align*}
\frac{d\langle a \rangle}{dt} &= -(\kappa/2 + i\delta)\langle a \rangle - i\epsilon_{in} - ig\langle \sigma_- \rangle \\
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\frac{d\langle \sigma_m \rangle}{dt} &= ig(\langle a\sigma_+ \rangle - \langle a^\dagger\sigma_- \rangle) + \sum_{i \neq m} \Gamma_{mi}\langle \sigma_i \rangle - \sum_{i \neq m} \Gamma_{im}\langle \sigma_m \rangle \\
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\end{align*}
\]

J.J. Viennot et al. (arXiv:1310.4363)
Driving the effective spin out of equilibrium

\[
\frac{d\langle a \rangle}{dt} = -\left(\kappa/2 + i\delta\right)\langle a \rangle - i\epsilon_{in} - ig\langle \sigma_- \rangle
\]

\[
\frac{d\langle \sigma_- \rangle}{dt} = -\left(\gamma/2 + \Gamma_{\phi} + i\Delta\right)\langle \sigma_- \rangle + ig\langle a \sigma_\pm \rangle
\]

\[
\frac{d\langle \sigma_\pm \rangle}{dt} = -ig\langle a \sigma_\pm \rangle + \sum_{i\neq p} \Gamma_{pi}\langle \sigma_i \rangle - \sum_{i\neq p} \Gamma_{ip}\langle \sigma_p \rangle
\]

\[
\frac{d\langle \sigma_m \rangle}{dt} = ig\langle a \sigma_\pm \rangle + \sum_{i\neq m} \Gamma_{mi}\langle \sigma_i \rangle - \sum_{i\neq m} \Gamma_{im}\langle \sigma_m \rangle
\]

\[
\frac{d\langle \sigma_j \rangle}{dt} = \sum_{i\neq j} \Gamma_{ji}\langle \sigma_i \rangle - \sum_{i\neq j} \Gamma_{ij}\langle \sigma_j \rangle
\]

\[
\Delta = \Omega - \omega_d \text{ and } \delta = \omega_0 - \omega_d
\]

\[
\Delta f = \text{Re}[\chi]\langle \sigma_z \rangle
\]

\[
\chi = \frac{(g_0 \sin \theta)}{-i(\gamma/2 + \Gamma_{\phi}) + \Delta}
\]

\[
\langle \sigma_z \rangle = -1
\]

J.J. Viennot et al. (arXiv:1310.4363)
Towards CNT-based quantum information devices

J.J. Viennot et al. (arXiv:1310.4363)
See also, in SC Nanowires and 2DEG:
The effective spin picture

- Quantitative agreement with the theory for \( \langle \sigma_z \rangle = -1 \)
- We extract \( g_0 \) from 3MHz to 12MHz
- We extract \( \gamma/2 + \Gamma_\phi \) from 450MHz to 3GHz

\[ \Omega \sim 6 \text{ GHz} \]
\[ \omega_0 = 6.721 \text{ GHz} \]
\[ Q \sim 3500 \]

J.J. Viennot et al. (arXiv:1310.4363)
See also, in SC Nanowires and 2DEG:
Out of equilibrium charge Qbit

Bias pumping:

J.J. Viennot et al. (arXiv:1310.4363)
Out of equilibrium charge Qbit

Bias pumping:

\[ \Delta \varphi \sim \text{Re}(\chi) \langle \sigma_Z \rangle \]
\[ \langle \sigma_Z \rangle \approx -1 \]

\( V_{g2} \) (mV)

\( V_{sd} = 50\mu V \)

J.J. Viennot et al. (arXiv:1310.4363)
Out of equilibrium charge Qbit

Bias pumping:

\[ \Delta \phi \sim \text{Re}(\chi) \langle \sigma_Z \rangle \]

\[ \langle \sigma_Z \rangle \neq -1 \]

- Direct measurement of \( \langle \sigma_Z \rangle \) in a transport situation (not equivalent to current)
- Good agreement between theory and experimental data -> extract relaxation rates

J.J. Viennot et al. (arXiv:1310.4363)
Out of equilibrium charge Qbit

Photons reduce in a manner directly related to the internal relaxation rate and the number of photons in the cavity.

Quantitative agreement with theory (red line)

\[ \langle \sigma_Z \rangle = \frac{-1}{1 + 4\mathcal{S}m[\chi]n_{ph}/\gamma} \]

Number of photons in the cavity

AB/B relaxation rate

\( n_{ph} \sim 40 \quad \gamma \sim 300\text{MHz} \)

J.J. Viennot et al. (arXiv:1310.4363)
Towards spin-photon coupling?

Only charge coupling so far  \rightarrow  Weak coupling regime

\[ g_{\text{charge}} \approx 3 - 12 \text{ MHz} \]
\[ T_{2\text{ charge}}^* \approx 0.3 - 3 \text{ ns} \]

Use of dephasing model at second order in detuning fluctuations (semiclassical)

\[ \Gamma^*_\phi \approx \frac{d^2 \Omega}{d \epsilon^2} \langle \sigma_\epsilon \rangle^2 = \frac{\langle \sigma_\epsilon \rangle^2}{2t} \]

Charge noise \( \sim \frac{6 - 15 \times 10^{-4} e}{\sqrt{HZ}} \)  \rightarrow  Important for spin/valley quantum control!
Towards spin-photon coupling?

Only charge coupling so far $\rightarrow$ Weak coupling regime

weak coupling regime

Strong coupling? $g > \Delta f_{\text{cavity}}, \frac{1}{T^*_2}$

Spin-Photon coupling mechanism?

$g_{\text{charge}} \approx 10 - 50 \text{ MHz}$

$T^*_{\text{charge}} \approx 0.3 - 3 \text{ ns}$
Towards spin-photon coupling?

Only charge coupling so far → Weak coupling regime

\[ g_{\text{charge}} \approx 10 - 50 \text{ MHz} \]
\[ T_{2 \text{ charge}}^* \approx 0.3 - 3 \text{ ns} \]

Strong coupling? \[ g > \Delta f_{\text{cavity}}, \quad \frac{1}{T_{2}^*} \]

Spin-Photon coupling mechanism?
General principle of the ferromagnetic spin Qbit

General principle of the ferromagnetic spin Qbit

General principle of the ferromagnetic spin Qbit

Engineering non-collinear ferromagnets

AFM (tapping amplitude)
Engineering non-collinear ferromagnets

AFM (tapping amplitude)  MFM (phase, 70nm)

PdNi

SWNT

Magnetisation

S  Vg1  Vg2  D

AlOx

Vgt
Preliminary Results

Signature of active ferromagnetic interfaces (MR~45%)
✓ Coupling to charge Qbit, at resonance, in a *nuclear spin-free host material*

✓ Out of equilibrium susceptibility measurement

Single Spin-Photon coupling in circuit-QED?
• Prediction of strong and switchable coupling for the ferromagnetic spinQbit

Other perspectives compatible with such an architecture:
• Decoherence study in strongly correlated systems
• Non-local effects in superconducting hybrid structures
• Quantum simulation of Anderson-Holstein physics
• ...
Outline

I. Out of equilibrium charge dynamics in a cQED architecture
II. Mesoscopic conductors in a cQED architecture
III. Non-collinear magnetoelectronics with a quantum dot
Simplest paradigm for charge dynamics in a coherent conductor

Universal relaxation resistance in a weakly interacting quantum dot in the coherent regime (Gamma’s >> kT)

The quantum RC circuit

- Simplest paradigm for charge dynamics in a coherent conductor
- Universal relaxation resistance in a weakly interacting quantum dot in the coherent regime ($\Gamma's \gg kT$)


The quantum RC circuit

- Single wall carbon nanotube « connected » only to one metallic contact
- Use of cavity read-out only here (no DC current)

L.E. Bruhat et al. in preparation
No DC current here (only one contact) but phase and amplitude contrast

Resonant levels in the nanotube lead to peaks in phase and amplitude

Positive slope show that one of the two metallic contact acts like a reservoir

L.E. Bruhat et al. in preparation
Amplitude change is a direct measurement of charge relaxation.

Cavity frequency shift is a direct measurement of dot’s capacitance.

LC resonator and quantum RC circuit in parallel.

L.E. Bruhat et al. in preparation
Power evolution of phase peak allows to measure the electron-photon coupling.

Adiabatic peak modulation here (\(\Gamma >> \omega_0\)).

Coupling strength consistent with previous measurements (about 100 MHz).

L.E. Bruhat et al. in preparation.
Phase contrast corresponds to a strongly renormalized capacitance (OK if interactions)

Relaxation account for by non-interacting theory with no adjustment parameter

Non universal relaxation resistance (violation of Korringa-Shiba identity)

L.E. Bruhat et al. in preparation
Phase contrast corresponds to a strongly renormalized capacitance (OK if interactions)

Relaxation account for by non-interacting theory with no adjustment parameter

Non universal relaxation resistance (violation of Korringa-Shiba identity)

Can we expand this method to more exotic mesoscopic systems?
Majorana systems in cavities

T. Hyart et al., PRB 88, 035121 (2013),
C. Müller, J. Bourassa and A. Blais, arXiv 1306.1539
E. Ginossar and E. Grosfeld, arXiv 1307.1159


Coupling to cavity mediated by a superconducting quantum bit
4-Majorana bound states system

\[ \mu_c / \Delta = 1.73 \]

Topological sections: \( \mu_1 < \mu_c \)

Non-topological sections: \( \mu_0 > \mu_c \)

Majorana operators:
\[ \gamma_i = \gamma_i \quad \gamma_i^2 = 1/2 \]
\[ i \in \{1, 2, 3, 4\} \]

Nanowire eigenenergies:
\[ H_{wire} = 2i\epsilon (\gamma_1 \gamma_2 + \gamma_3 \gamma_4) + 2i\bar{\epsilon} \gamma_2 \gamma_3 \]

\[ \epsilon \approx \lambda_\epsilon e^{-|k(\mu_1)|L_T} \]
\[ \bar{\epsilon} \approx \lambda_{\bar{\epsilon}} e^{-|k(\mu_0)|L_{NT}} \]
Conductance of the nanowire

$$H_{\text{wire}} = 2i\epsilon(\gamma_1\gamma_2 + \gamma_3\gamma_4) + 2i\tilde{\epsilon}\gamma_2\gamma_3$$

$$H_c = \sum_p \epsilon_p c_p^\dagger c_p + t(c_p^\dagger - c_p)\gamma_1$$

See for instance Flensberg, PRB (2010) for the conductance calculation.
Effect of $\mu_1$ on the transverse coupling

The disappearance of the transverse coupling for $\mu_1$ far below $\mu_c$ is a direct consequence of the self-adjoint character of Majorana fermions.
Experimental signatures of the Transverse coupling

Realistic parameters: Cottet, Kontos & Douçot, arXiv:1307.4185

\[ \Delta = 250 \ \mu eV \]
\[ E_z = 500 \ \mu eV \]
\[ \alpha_{so} = 4 \times 10^4 \ \text{m.s}^{-1} \]
\[ L_{T(NT)} = 1 \ \mu m \]
\[ \alpha_c V_{rms} = 2 \ \mu V \]
\[ \omega_{cav}/2\pi = 4 \ \text{GHz} \]

\[ \Rightarrow \mu_c/\Delta = 1.73 \]

\[ \chi : \text{cavity dispersive frequency shift} \]
\[ K : \text{amplitude of nonlinear Kerr term} \]

The evolutions of \( \chi \& K \) reveal \( \gamma_i^\uparrow = \gamma_i \) & the exponential confinement of MBSs
Measuring the cavity nonlinearity $K$

\[ P_{in}^c \propto |K|^{-1} \propto e^{2|\kappa_m(\mu_1)|L_T} \]

Cavity tomography at a time $\Delta t$ after switching off the input power.
Study of the quantum RC circuit problem
- Non-interacting theory account with no adjustable parameter for relaxation... but capacitance renormalized by interaction (non-universal relaxation)

Generalization to more exotic electronic states
- Detection of self-adjoint character of Majorana’s
- Squeezing of (microwave) light due to large Majorana-photon coupling
I. Out of equilibrium charge dynamics in a cQED architecture
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A non-collinear spin valve with a nanotube

- Electrical injection and detection of spins in the nanotube.
- Study as a function of $V_{SD}$, $V_G$ and external $B$.
- Non-collinear magnetizations obtained geometrically ($B$ along easy axis of one of the magnetizations)
Characterization of the device

- Coulomb diamonds of a rather open and asymmetric Qdot
- Spin valve like signal of about 4%

A.D. Crisan et al. in preparation
Spin signal in the linear regime

Oscillations of TMR with the same period as G

Standard behavior of a quantum dot spin valve (but no sign change)

TMR and G slightly out of phase but TMR not derivative of G (no magnetocoulomb)

See also: S. Sahoo et al. Nature Phys’05, H.T. Man et al PRB(R)’06
C. Feuillet-Palma et al. PRB’10

A.D. Crisan et al. in preparation
Spin signal in the nonlinear regime

- Sign change of TMR as bias is reversed
- Nearly antisymmetric TMR as a function of bias
- Same symmetry as current

A.D. Crisan et al. in preparation
Spin signal in the nonlinear regime

\[ \vec{B} = B_L \vec{n}_L + B_R \vec{n}_R \]

\[ \frac{d S}{dt} = \frac{\hbar}{2e} p I (\vec{n}_L - \vec{n}_R) + \vec{S} \times \vec{B} - \frac{\vec{S}}{\tau_s} \]

\[ S_{L(R)} = \frac{\hbar}{2e} p (1 - \cos \phi) I \tau_s \times \frac{1}{1 + (\omega_L \tau_s)^2 (\sin \phi)^2} \]

Spin accumulation

Hanle term

See e.g.: W. Wetzels, M Grifoni and G.E.W. Bauer PRB’06

- Phenomenological Bloch-Redfield type equation for the spin of the dot
- Competition between spin accumulation, spin precession and relaxation
- We assume that the interface fields are negligible

A.D. Crisan et al. in preparation
Spin signal in the nonlinear regime

- Quantitative agreement with simple spin accumulation/spin precession model
- Main ingredient is bias dependence of relaxation time $\tau_s \approx \tau_0 / (1 + (V_{sd}/V_0)^2)^2$
- Low bias proportional to current as expected from spin accumulation

A.D. Crisan et al. in preparation
Spin signal in the nonlinear regime

- Slope of white line correspond to a «g» factor between 200 and 700 !
- Cannot be explained by Zeeman and/or orbital effect
- Spin precession model naturally explain it with reasonable spin relaxation time

A.D. Crisan et al. in preparation
Strong correlations between $1/g$ and dot’s conductance

Effective «$g$» is strongly gate dependent

Strong correlations between $1/g$ and dot’s conductance

Intuitively expected because higher conductance should give higher spin relaxation rate...

A.D. Crisan et al. in preparation
Study of spin transport in a quantum dot in non-collinear regime
- simple spin precession model explains the data
- consistent with reasonable spin relaxation time
Coupling a microwave cavity to an open system

\[ \Gamma \gg f_{\text{cavity}} \]

Adiabatic modulation of conductance peak

\[ \Delta E = 2g\sqrt{n} \]

\[ g = g_0 + f\left(\frac{\Gamma}{U}\right) \]

- Coupling depends on geometric and quantum capacitances
- Coupling via the leads is dominant

M.R. Delbecq et al. PRL (2011)
Two single quantum dots in a microwave cavity

- QD1 and QD2 are read-out via the phase of the microwave signal
- Vertical lines slightly tilted (QD1)
- QD2 levels are controlled both by gate $V_{g2}$ and distant gate $V_{g1}$
- The slope of the closed dot levels is much larger than the slope of the open dot

Two single quantum dots in a microwave cavity

**Experiment**

**Qualitative Model**

Polaronic shift of energy levels:

\[
\delta \varepsilon_2 = -2 \frac{g_1(V_{g1})g_2(V_{g2})}{\omega_0} N_{el,QD1} \approx 1 \text{meV}
\]

- \(N \approx 10^4\) on the open dot (QD1)
- All cavity modes up to \(\Gamma\)’s matter (\(\approx 100\))

The gate dependence of the \(g\)’s provide the mechanism for the dispersion of levels

Principle of the ferromagnetic spin Qubit

\[ \vec{m}_L, \; \vec{m}_R \]

\[ \theta = \frac{\pi}{6} \]

\( t=0 \)

\( (\emptyset, \uparrow) \)
\( (\uparrow, \emptyset) \)

\( n_g^L, n_g^R \)

\( n_g^L \): reduced gate voltages for dot L(R)

\[ \text{dashed lines: } t=0 \]
\[ \text{full lines: } t=2\delta/3 \]

\[ (\emptyset, \sqrt{1}) \]
\[ (\emptyset, \emptyset) \]
\[ (\uparrow, \emptyset) \]

\[ (\emptyset, \uparrow) \]

\[ (\downarrow, \emptyset) \]

\[ (\uparrow, \emptyset) \]

\[ (\uparrow, \sqrt{1}) \]

Hamiltonian of the ferromagnetic spin Qbit

\[ \hat{H} = \begin{bmatrix}
-\delta_L & 0 & t\cos[\theta/2] & -t\sin[\theta/2] \\
0 & +\delta_L & t\sin[\theta/2] & t\cos[\theta/2] \\
t\cos[\theta/2] & t\sin[\theta/2] & -\delta_R + D & 0 \\
-t\sin[\theta/2] & t\cos[\theta/2] & 0 & +\delta_R + D
\end{bmatrix} \]

- \(D\) is controlled by \(V_{g_L}^L, V_{g_R}^R\) and possibly \(V_{ac}\)
- \(2\delta_L(R)\): effective Zeeman splitting in dot L(R)
- \(t\) = hoping between left & right dot
- We assume \(\delta_L = \delta_R = \delta\) for simplicity
Carbon nanotube as a good coherent conductor

No nuclear spins
Dephasing only due to charge noise

$D_{\text{ON}} = 2.8 \delta$, $g_{\text{ON}} = 5.6 \text{MHz}$, $T_2 = 1.2 \mu s$ $\rightarrow$ strong coupling regime reached

$D_{\text{OFF}} = 20 \delta$, $g_{\text{OFF}} = 13 \text{kHz}$, $T_2 = 2 \text{ms}$ $\rightarrow$ quantum register at the OFF point

Strongly tunable Spin/Photon coupling

Dephasing due to low-frequency charge noise


Charge noise mediated by fluctuations of $D$

\[
\nu_{01} \sim 2\delta_L
\]

ON point: $T^D_\varphi \sim 2.9 \mu s$

OFF point: $T^{D}_\varphi \simeq 2$ ms

ON and OFF points: $T^{\delta_L}_\varphi = 15$ ms

Chemical potential of dot L (meV)
Relaxation due to phonons

- Stretching vibrons confined in dots L and R

- Vibron frequencies \( \nu_p = p \times 100 \text{ GHz}, \ p \in \mathbb{N} \)

- Vibron damping \( Q_{ph} = \frac{h \nu_{ph}}{\Gamma} \rightarrow \) analogy with Purcell effect

\[
\frac{1}{T_1} = \sum_{l \in \{L,R\},\ \ p \in \mathbb{N}} \frac{\hbar \tilde{g}_{l,p}^2 \Gamma}{(\frac{\Gamma}{2})^2 + (h \nu_p - h \nu_{01})^2}
\]

\( \tilde{g}_{l,p} \): electron/vibron coupling

**Non-suspended carbon nanotube:**

\[
T_1^{ON} \simeq 1.0 \mu s \text{ and } T_1^{OFF} \simeq 0.21 \text{ s} \quad \text{for } Q_{ph} = 1.5
\]

**Suspended carbon nanotube:**

\[
T_1^{ON} \simeq 14 \mu s \text{ and } T_1^{OFF} \simeq 2.8 \text{ s} \quad \text{for } Q_{ph} = 20
\]