Sweep a qubit to entangle states and to gauge its environment

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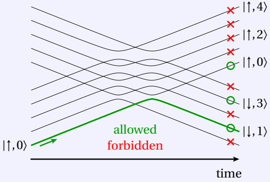
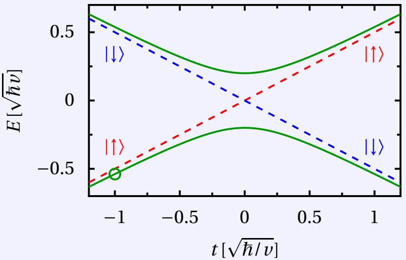


in collaboration with

M. Wubs (Copenhagen), S. Kohler (Madrid)

K. Saito (Tokyo), Y. Kayanuma (Osaka), D. Zueco (Zaragoza)

prologue: the "standard" Landau-Zener problem



Landau, Zener, Stückelberg, Majorana (1932)

time-dependent two-level system

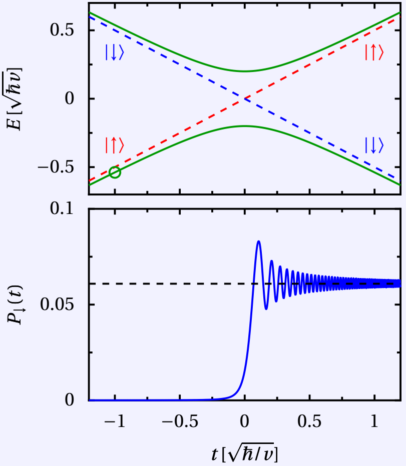
$$H(t) = -\frac{vt}{2}\sigma_z + \frac{\Delta}{2}\sigma_x$$

- diabatic states: $|\uparrow\rangle$, $|\downarrow\rangle$
- adiabatic states

“standard” Landau-Zener problem

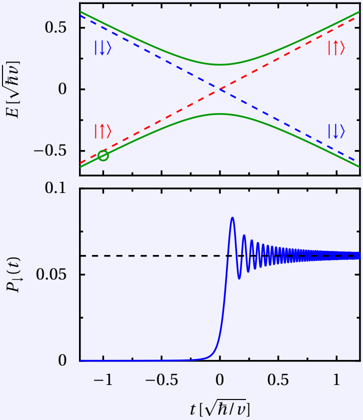
finite times: numerical & analytical

(parabolic cylinder functions)



"standard" Landau-Zener problem

finite times: numerical



$t \to \infty$: analytical

- transition probability

$$P_{\uparrow\to\downarrow}(\infty) = 1 - \exp\left(-\frac{\pi\Delta^2}{2\hbar v}\right)$$

- large splitting Δ:
  adiabatic following, $P_{\uparrow\to\downarrow}(\infty) = 1$

Landau, Zener, Stückelberg, Majorana (1932)

alternative: complete summation of a perturbation series in $\frac{\Delta}{2}\sigma_x$

Kayanuma (1984)

quantum information:

- qubit: two-level system $|\uparrow\rangle$, $|\downarrow\rangle$
- quantum gates: unitary operations

Landau-Zener transitions relevant for …

- ✓ gate operations
- ✓ manipulation of qubits
- ✓ quantum state preparation
- ✓ adiabatic quantum computing
- ✓ …

PHYSICAL REVIEW A 69, 062320 (2004)

Cavity quantum electrodynamics for superconducting electrical circuits: An architecture for quantum computation

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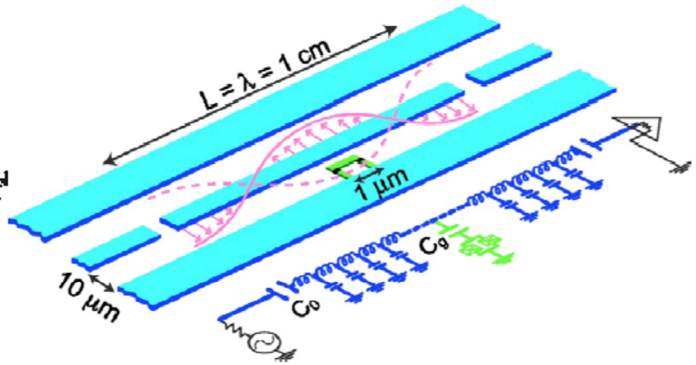
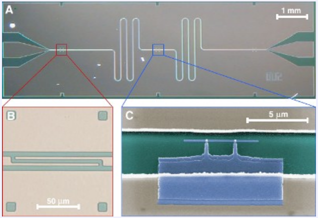


TABLE I. Key rates and CQED parameters for optical [2] and microwave [3] atomic systems using 3D cavities, compared against the proposed approach using superconducting circuits, showing the possibility for attaining the strong cavity QED limit ($n_{\mathrm{Rabi}} \gg 1$). For the 1D superconducting system, a full-wave ($L=\lambda$) resonator, $\omega_r/2\pi = 10$ GHz, a relatively low Q of 10^4, and coupling $\beta = C_g/C_\Sigma = 0.1$ are assumed. For the 3D microwave case, the number of Rabi flops is limited by the transit time. For the 1D circuit case, the intrinsic Cooper-pair box decay rate is unknown; a conservative value equal to the current experimental upper bound $\gamma \leqslant 1/(2\ \mu\mathrm{s})$ is assumed.

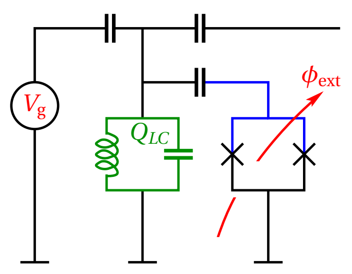
Parameter	Symbol	3D optical	3D microwave	1D circuit
Resonance or transition frequency	$\omega_r/2\pi$, $\Omega/2\pi$	350 THz	51 GHz	10 GHz
Vacuum Rabi frequency	g/π, g/ω_r	220 MHz, 3×10^{-7}	47 kHz, 1×10^{-7}	100 MHz, 5×10^{-3}
Transition dipole	d/ea_0	~1	1×10^{3}	2×10^{4}
Cavity lifetime	$1/\kappa, Q$	10 ns, 3×10^{7}	1 ms, 3×10^{8}	160 ns, 10^{4}
Atom lifetime	$1/\gamma$	61 ns	30 ms	2 μs
Atom transit time	t_{transit}	$\geqslant 50\ \mu$s	100 μs	∞
Critical atom number	$N_0 = 2\gamma\kappa/g^2$	6×10^{-3}	3×10^{-6}	$\leqslant 6\times10^{-5}$
Critical photon number	$m_0 = \gamma^2/2g^2$	3×10^{-4}	3×10^{-8}	$\leqslant 1\times10^{-6}$
Number of vacuum Rabi flops	$n_{\mathrm{Rabi}} = 2g/(\kappa+\gamma)$	~10	~5	$\sim10^{2}$

circuit QED



A. Wallraff *et al.*, Nature'04

solid-state analogue of
a two-level atom
in an optical resonator
(cavity QED)



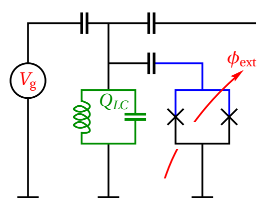
Cooper-pair box = charge qubit

resonator = (*LC*) oscillator

tuneable parameters:

gate voltage V_g
magnetic flux ϕ_{ext}

circuit QED



Blais *et al.* (2004)

Wallraff *et al.* (2004)

- resonator as LC oscillator: $H = \hbar\Omega b^\dagger b$
- Cooper-pair box (CPB):
  charging energy

$$H_{el} = 4E_C(\hat{N} - N_g)^2, \quad N_g = \frac{C_g V_g}{2e}$$

  Josephson energy:

$$H_J = -\frac{E_J}{2}\cos\left(\frac{2\pi\phi_{ext}(t)}{\phi_0}\right)\sum_N \Big(|N\rangle\langle N+1| + |N+1\rangle\langle N|\Big)$$

- CPB-oscillator coupling: $H_{int} = \gamma(b^\dagger + b)\hat{N}$

$E_C \gg E_J$ and $N_0 \leq N_g \leq N_0 + 1$

➔ charge qubit: effective two-state system $|N_0\rangle, |N_0 + 1\rangle$

"computational basis" in charge-degeneracy point $N_g = N_0 + 1/2$:

$$|\uparrow\rangle = \frac{|N_0\rangle + |N_0+1\rangle}{\sqrt{2}} \qquad |\downarrow\rangle = \frac{|N_0\rangle - |N_0+1\rangle}{\sqrt{2}}$$

so that

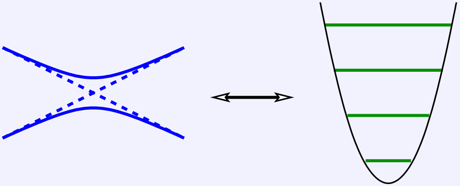
$$\boxed{H = \frac{vt}{2}\sigma_z + \gamma(b^\dagger + b)\sigma_x + \hbar\Omega b^\dagger b}$$

typical parameter values:

- maximal Josephson energy $E_{J,max}/\hbar = vt_{max}/\hbar$: 10^{10} Hz, minimal switching time: 1μs
- oscillator frequency Ω: 10^8–10^9 Hz
- coupling strength $\gamma/2\pi\hbar$: 10^6–10^7 Hz; $\gamma/2\pi\hbar\Omega \simeq 10^{-3}$–$10^{-2}$
- [compare atom in cavity: $\gamma/2\pi\hbar\Omega \lesssim 10^{-6}$]

Sweep a qubit to entangle states and to gauge its environment

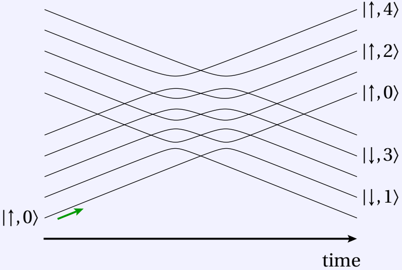
coupling to a single quantum oscillator



Saito, Wubs, Kohler, Hänggi, Kayanuma, Europhys. Lett. **76**, 22 (2006)

qubit coupled to a single quantum oscillator

adiabatic energies:

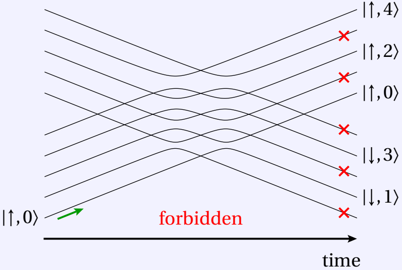


$$H(t) = \frac{vt}{2}\sigma_z + \gamma\sigma_x(b^\dagger + b) + \hbar\Omega b^\dagger b$$

- diabatic states: $|\uparrow, n\rangle$, $|\downarrow, n\rangle$
- initial state: $|\uparrow, 0\rangle$
  (diabatic ground state)
- coupling $\sigma_x(b^\dagger + b)$
  selection rule: $|\uparrow, 2\ell + 1\rangle$ and $|\downarrow, 2\ell\rangle$ never populated

qubit coupled to a single quantum oscillator

adiabatic energies:



$$H(t) = \frac{vt}{2}\sigma_z + \gamma\sigma_x(b^\dagger + b) + \hbar\Omega b^\dagger b$$

- diabatic states: $|\uparrow, n\rangle$, $|\downarrow, n\rangle$
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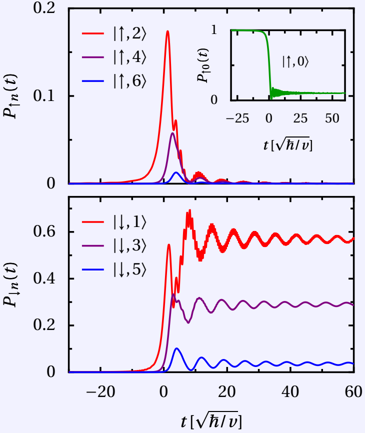
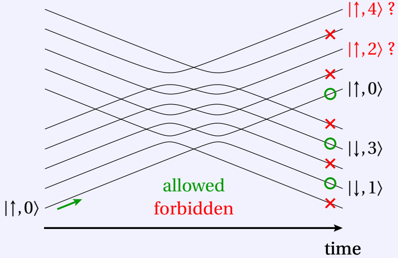
- coupling $\sigma_x(b^\dagger + b)$
  selection rule: $|\uparrow, 2\ell + 1\rangle$ and $|\downarrow, 2\ell\rangle$ never populated

dynamics: numerical solution



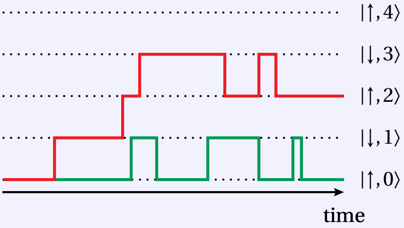
- all $|\uparrow, n \neq 0\rangle$ finally unpopulated
- selection rule for odd n only



? hidden selection rule **?**

qubit + oscillator: perturbation series

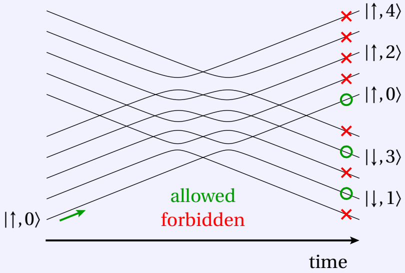
series for $\langle\uparrow, n|U(\infty,-\infty)|\uparrow,0\rangle$ with perturbation $H_{\text{int}} = \gamma\sigma_x(b^\dagger + b)$



- Generalization of method by Kayanuma (1984)
- no contribution to $\langle\uparrow, n|U(\infty,-\infty)|\uparrow,0\rangle$
- only contribution: repeated jumps between $|\uparrow,0\rangle$ and $|\downarrow,1\rangle$

Volkov & Ostrovsky ('05); Dobrescu & Sinitsyn ('06); Saito *et al.* ('06)

no-go theorem



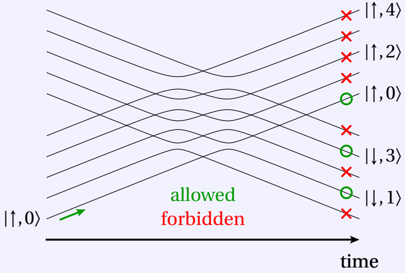
consequences:

1. no-go theorem for $t \to \infty$
2. perturbation series for $P_{\uparrow\to\uparrow}$ consists of only the states $|\uparrow,0\rangle$ and $|\downarrow,1\rangle$
   - ➔ no-go theorem for series
   - ➔ same perturbation series as for standard LZ problem with $\Delta/2 \longrightarrow \gamma$

$$P_{\uparrow\to\downarrow}(\infty) = 1 - \exp\left(-\frac{2\pi\gamma^2}{\hbar v}\right)$$

Saito, Wubs, SK, Hänggi, Kayanuma, EPL **76**, 22 (2006)

no-go theorem



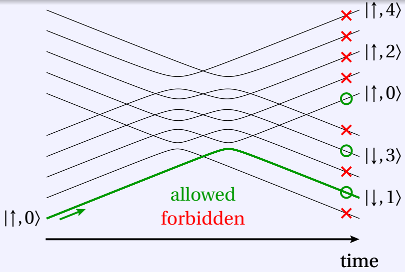
consequences:

1. "no-go-up theorem" for $t \to \infty$
2. perturbation series for $P_{\uparrow\to\uparrow}(\infty)$ involves only $|\uparrow,0\rangle$ and $|\downarrow,1\rangle$
   ➔ same series as for standard LZ problem

$$P_{\uparrow\to\uparrow}(\infty) = \exp\left(-\frac{2\pi\gamma^2}{\hbar v}\right)$$

3. beyond RWA, but …
   independent of frequency Ω

quantum state preparation: single-photon generation

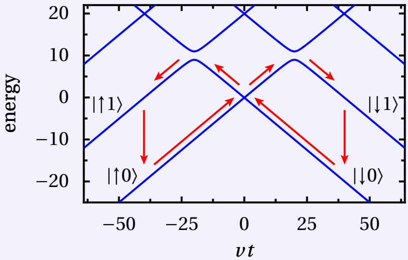


- $\gamma \ll \hbar\Omega$
- slow sweep ($v \ll \gamma^2/\hbar$)

  ➔ $|\uparrow,0\rangle \rightarrow |\downarrow,1\rangle$

  single-photon generation

  $P_{\uparrow\rightarrow\downarrow} = 1$

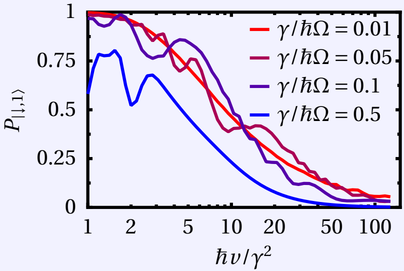


- slow sweep + cavity decay

  ➔ "single-photon-cycle"

K. Saito, M. Wubs, S. Kohler, P. Hänggi, Y. Kayanuma, Europhys. Lett. **76**, 22 (2006)

quantum state preparation: entanglement generation



- general sweep ➔

  $\psi(\infty) = \alpha(v)|\uparrow,0\rangle + \beta(v)|\downarrow,1\rangle$

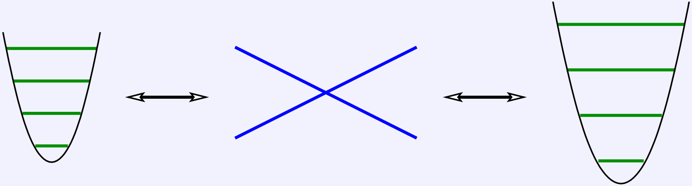
- controllable qubit-oscillator entanglement in circuit QED

- $P_{|\downarrow,1\rangle} = |\beta(v)|^2 = 1/2$ ➔
  qubit-oscillator Bell state

M. Wubs, S. Kohler, P. Hänggi, Physica E **40**, 187 (2007)

LZ sweeps in a qubit …

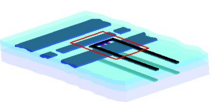
…coupled to two quantum oscillators



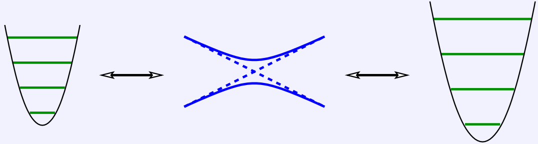
$$H(t) = \hbar\Omega b_1^\dagger b_1 + \gamma\sigma_x(b_1^\dagger + b_1) + \frac{vt}{2}\sigma_z + \gamma\sigma_x(b_2^\dagger + b_2) + \hbar(\Omega + \delta\omega) b_2^\dagger b_2$$

Wubs *et al.*, Physica E **40**, 187 (2007)

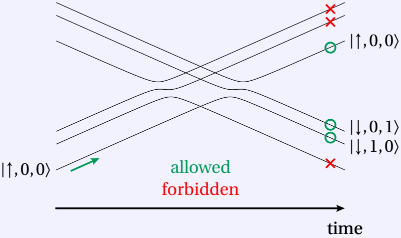
two transmission lines



R. Gross *et al.*, WMI Garching

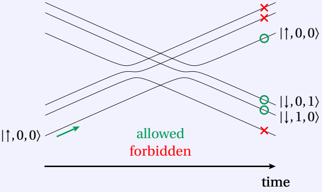


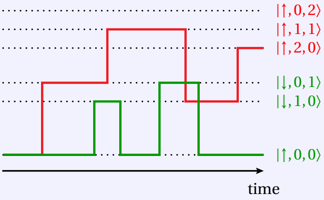
adiabatic energies:



- diabatic states:
  $|\uparrow,n_1,n_2\rangle, |\downarrow,n_1,n_2\rangle$
- initial state: $|\uparrow,0,0\rangle$

transition probability





no-go theorem:

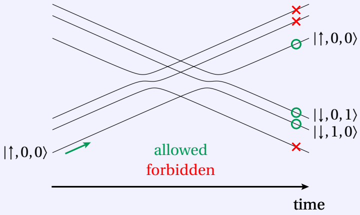
- forbidden: many-photon states
- only contribution: jumps between oscillator ground state and single-photon states

➔ spin-flip probability

$$P_{\uparrow\to\downarrow}(\infty) = 1 - \exp\left(-\frac{2\pi(\gamma_1^2+\gamma_2^2)}{\hbar v}\right)$$

application: quantum state preparation

for $g_i \ll \Omega_1 = \Omega_2$: $\quad |\psi_{\text{final}}\rangle = \alpha(v)|\uparrow,0,0\rangle + \beta(v)\big(|\downarrow,1,0\rangle + |\downarrow,0,1\rangle\big)$



- slow switching, $v \ll g^2/\hbar$: $\alpha(v) \approx 0$

  ➔ oscillator-oscillator entanglement

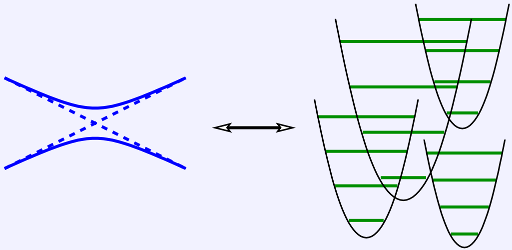
- intermediate v: $\alpha(v) = \beta(v) = \frac{1}{\sqrt{3}}$

  ➔ W state

Wubs, Kohler, Hänggi, Physica E **40**, 187 (2007)

Sweep a qubit to entangle states and to gauge its environment

coupling to a quantum heat bath



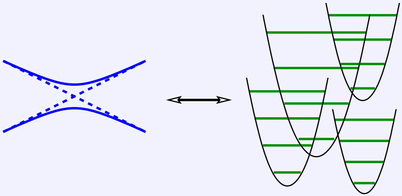
Caldeira-Leggett model: coupling to bath of harmonic oscillators

$$H = H_{\text{system}}(t) + X \sum_{\nu} \gamma_{\nu} (a_{\nu}^{\dagger} + a_{\nu}) + \sum_{\nu} \hbar\omega_{\nu} a_{\nu}^{\dagger} a_{\nu}$$

M. Wubs, K. Saito, S. Kohler, P. Hänggi, Y. Kayanuma, PRL **97**, 200404 (2006)

K. Saito, M. Wubs, S. Kohler, Y. Kayanuma, P. Hänggi, PRB **75**, 214308 (2007)

coupling to a quantum heat bath



$$H = -\frac{vt}{2}\sigma_z + \frac{\Delta}{2}\sigma_x$$
$$+ (\sigma_z \cos\theta + \sigma_x \sin\theta) \sum_\nu \gamma_\nu (a_\nu^\dagger + a_\nu)$$
$$+ \sum_\nu \hbar\omega_\nu a_\nu^\dagger a_\nu$$

- $\cos\theta \neq 0$: displaced oscillator ground states

  ➔ diabatic states $|\uparrow, \boldsymbol{n}_+\rangle$ and $|\downarrow, \boldsymbol{n}_-\rangle$,   note: generally $|\boldsymbol{n}_+\rangle \neq |\boldsymbol{n}_-\rangle$

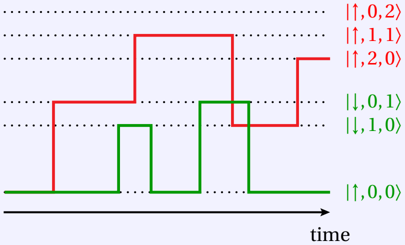
  ➔ reorganization energy $E_0 = \sum_\nu \frac{\gamma_\nu^2}{4\hbar\omega_\nu}$

- effective coupling strength $S = \sum_\nu \gamma_\nu^2$

- zero temperature: initially in ground state of system-plus-bath

generalization to many oscillators

e.g.: two oscillators



no-go-up theorem:
(initial state: $|\uparrow,0,0,\ldots\rangle$)

- no contribution: many-photon states
- only contribution: jumps between oscillator ground state and single-photon states

$$P_{\uparrow\to\uparrow}(\infty) = \exp\left(-\frac{2\pi\sum_\nu \gamma_\nu^2}{\hbar v}\right)$$

M. Wubs, S. Kohler, P. Hänggi, Physica E **40**, 187 (2007)

quantum heat bath

more general qubit-bath coupling:

$$H = \frac{vt}{2}\sigma_z + \frac{\Delta}{2}\sigma_x + (\sigma_z \cos\theta + \sigma_x \sin\theta)\sum_\nu \gamma_\nu (a_\nu^\dagger + a_\nu) + \sum_\nu \hbar\omega_\nu a_\nu^\dagger a_\nu$$

σ_z "longitudinal coupling" ⇔ $\theta = 0$

σ_x "transverse coupling" ⇔ $\theta = \pi/2$

- reorganization energy $E_0 = \sum_\nu \frac{\gamma_\nu^2}{\hbar\omega_\nu} = \frac{\hbar}{4\pi}\int_0^\infty \mathrm{d}\omega\, J(\omega)/\omega$
- integrated spectral density $S = \sum_\nu \gamma_\nu^2 = \frac{\hbar^2}{4\pi}\int_0^\infty \mathrm{d}\omega\, J(\omega)$
- zero temperature: initially in ground state of system plus bath

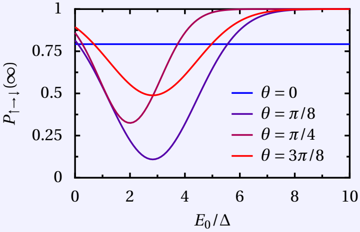
dissipative Landau-Zener transitions

- no-go-up theorem ➔ bath ends in ground state if qubit ends $|\uparrow\rangle$
- for $0 < P_{\uparrow\to\downarrow}(\infty) < 1$ ➔ qubit-bath entanglement
- transition probability

$$P_{\uparrow\to\uparrow}(\infty) = \exp\left(-\frac{\pi W^2}{2\hbar v}\right), \quad W^2 = \left(\Delta - E_0 \sin\theta\cos\theta\right)^2 + S\sin^2\theta$$

exact solution for a dissipative quantum system

M. Wubs, K. Saito, S. Kohler, P. Hänggi, Y. Kayanuma, PRL **97**, 200404 (2006)



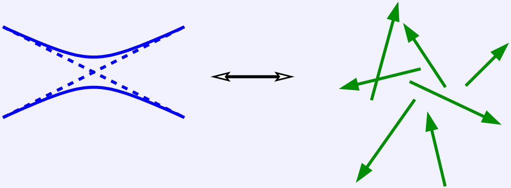
- dependence on
  - reorganization energy E_0
  - total coupling strength S
- vary Δ ➔ determine E_0, S

  $\ldots$unless $\theta = 0$, $\sin\theta = 0$

Sweep a qubit to entangle states and to gauge its environment

in the presence of a spin bath

. . . and beyond



Saito, Wubs, Kohler, Kayanuma, Hänggi, PRB **75**, 214308 (2007)

spin bath

general coupling to a spin bath

$$H = -\frac{vt}{2}\sigma_z + \frac{\Delta}{2}\sigma_x + \sum_{i=x,y,z}\sigma_i\sum_\nu \gamma_\nu^i \tau_\nu^i + \sum_\nu \sum_{i=x,y,z} B_\nu^i \tau_\nu^i$$

- no-go theorem ➔ exact spin-flip probability

special case:

- $\gamma_\nu^x = \gamma_\nu^y = 0$ corresponds to $\theta = 0$

$$H_{\text{qubit–env}} = \sigma_z \sum_\nu \gamma_\nu^i \tau_z^i$$

➔ $W^2 = \Delta^2$, i.e. Landau-Zener probability bath-independent

universality

? when is the LZ probability bath-independent **?**

generalized phase noise:

$$H(t) = -\frac{vt}{2}\sigma_z + \frac{\Delta}{2}\sigma_x + \sigma_z \mathscr{X} + H_{\text{env}}$$

for arbitrary environment H_{env} and bath operator $\mathscr{X}$

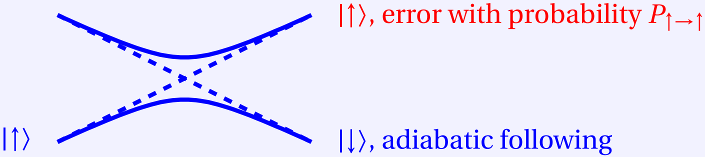
$$\boxed{P_{\uparrow\to\uparrow} = \exp\left(-\frac{\pi\Delta^2}{2\hbar v}\right) \qquad \text{for } T = 0}$$

➔ spin-flip probability bath-independent provided that

- H_{env} has a unique ground state
- the bath couples to σ_z only

adiabatic quantum computing:

- result encoded in ground state of a Hamiltonian H_f
- reach ground state by adiabatic time-evolution with
  $H(t)$ with $H(t_\mathrm{f}) = H_\mathrm{f}$
  ➔ requires ideal adiabatic following
- problem: LZ transitions at avoided crossings



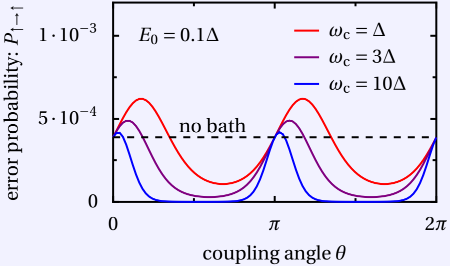
influence of heat bath ?

application: adiabatic quantum computing

$$P_{\uparrow\to\uparrow} = \exp\left(-\frac{\pi W^2}{2\hbar v}\right) \text{ with } W^2 = \left(\Delta - E_0 \sin\theta\cos\theta\right)^2 + S\sin^2\theta$$

- $W > \Delta$: bath supports adiabatic following
- $W < \Delta$: bath increases error probability

bath with ohmic spectral density: $J(\omega) \propto \omega e^{-\omega/\omega_c}$ ➔ $S = \hbar\omega_c E_0$



at zero temperature:

- $\theta = 0, \pi$: LZ probability bath-independent
- low cutoff frequency ➔ non-adiabatic transitions

temperature dependence

"general belief": thermal excitations support $|\uparrow\rangle \longrightarrow |\uparrow\rangle$

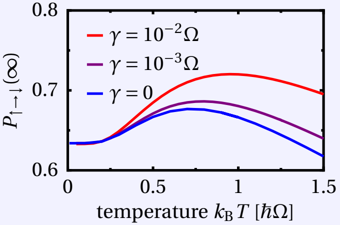
Ohmic phase noise, weak coupling — Ao & Rammer, PRL'89

classical noise — Kayanuma, PRB'98

spin bath — Wan & Amin, J.Quant.Inf.'09

➔ AQC error expected to increase with temperature

weak coupling: $g = 0.04\Omega$:



- non-monotonic T dependence

✓ adiabatic following improves for
  - larger damping γ
  - $k_B T \sim \hbar\Omega$

✗ … but not for $k_B T > \hbar\Omega$

➔ AQC error may decrease with kT

- cf. non-monotonic γ-dependence at finite kT

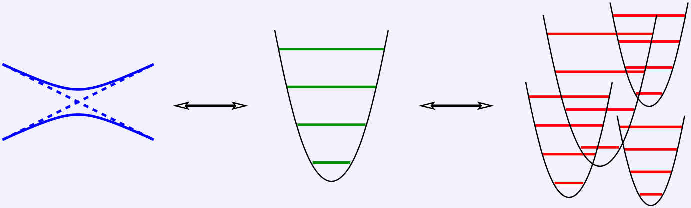
Nalbach & Thorwart, PRL (2009), Le Hur *et al.* PRA (2010), R.S. Whitney *et al.* PRL (2011)

Landau-Zener tunneling in qubit-oscillator settings

- exact LZ transition probability for ground state
- quantum state preparation in circuit QED
  - single-photon generation
  - Bell states, W states
- dissipative LZ transitions at $T = 0$
  - adiabatic quantum computing
  - spin bath
- qubit-oscillator-bath at finite T
  - non-monotonic temperature dependence

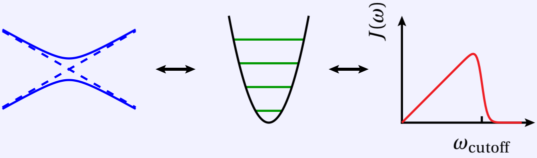
so far:

coupling to a dissipative oscillator

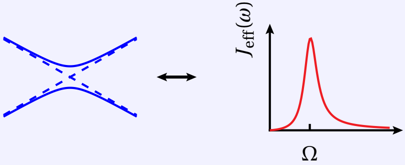


Zueco, Hänggi, SK, New J. Phys. **10**, 115012 (2008)

effective spectral density



- diagonalize oscillator-bath Hamiltonian



➔ qubit plus bath with peaked spectral density

➔ exact solution for $P_{\uparrow\to\downarrow}$ at $T = 0$

? oscillator dynamics

? finite temperatures

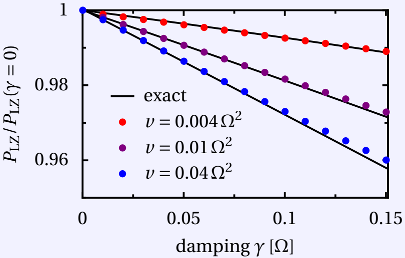
Bloch-Redfield master equation

- bath elimination

➔ master equation for qubit + oscillator

$$\frac{\mathrm{d}}{\mathrm{d}t}\rho = -\frac{\mathrm{i}}{\hbar}[H_{\mathrm{qubit}}(t) + H_{\mathrm{osc}}, \rho] + \mathscr{L}_{\mathrm{diss}}[\rho]$$

- note: $\mathscr{L}_{\mathrm{diss}}$ depends on qubit+oscillator dynamics



test case:

- zero temperature
- weak q-osc coupling: $g = 0.04\Omega$

✓ reliable for $\gamma \lesssim 0.1\Omega$
(error < 1%)

- Roland Doll
  Sigmund Kohler (Augsburg)
- Martijn Wubs (Copenhagen)
- Keiji Saito (Tokyo)
- Yosuke Kayanuma (Osaka)

This talk based on:

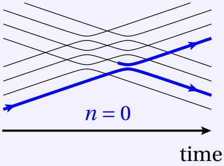
K. Saito, M. Wubs, S. Kohler, P. Hänggi, Y. Kayanuma, EPL **76**, 22 (2006)

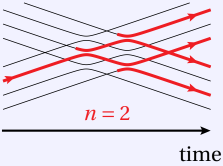
M. Wubs, K. Saito, S. Kohler, P. Hänggi, Y. Kayanuma, PRL **97**, 200404 (2006)

K. Saito, M. Wubs, S. Kohler, Y. Kayanuma, P. Hänggi, PRB **75**, 214308 (2007)

M. Wubs, S. Kohler, P. Hänggi, Physica E (in press); cond-mat/0703425 thermally occupied initial state $|\uparrow, n\rangle$

- narrowly avoided crossings
- weak damping and weak coupling

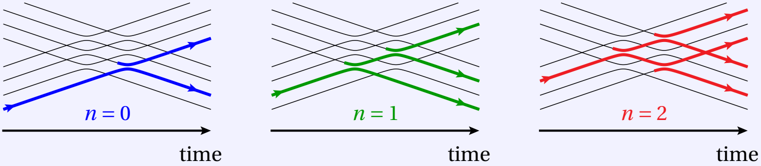




temperature dependence

thermally occupied initial state $|\uparrow, n\rangle$

- narrowly avoided crossings
- weak damping and weak coupling

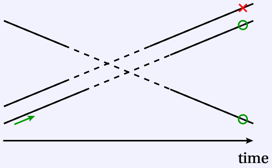


- $|\uparrow, 1\rangle$ has additional path to $|\downarrow\rangle$
- $n = 1$ most relevant for $k_B T \sim \hbar\Omega$

➔ $P_{\uparrow\to\downarrow}$ larger at intermediate temperatures

no-go theorem

three-level Landau-Zener problem



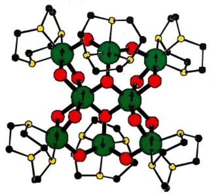
- upper level finally never populated ➔ "no-go theorem"

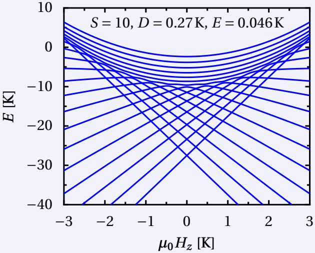
  Brundobler & Elser (1993)

  Shytov (2004); Volkov & Ostrovsky (2005)

- here:
  - generalization to (infinitely) many states
  - corollary: "no-go theorem" for perturbation series

application to nanomagnets





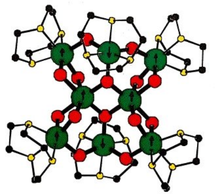
- molecular Fe_8 cluster, spin $S = 10$

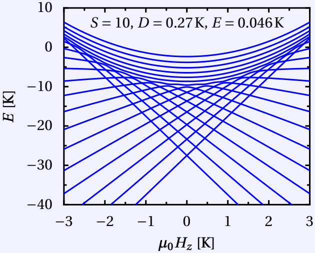
$$H = -DS_z^2 + E(S_x^2 - S_y^2) + g\mu_0 \vec{S} \cdot \vec{H}(t)$$

- determination of the very small splittings by LZ transitions
  Wernsdorfer & Sessoli, Science (1999)

- implicit assumption:
  individual LZ transition probabilities independent of dephasing
  Leuenberger & Loss, PRB (2000)

application to nanomagnets





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  individual LZ transition probabilities independent of dephasing
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- proof for $T = 0$ (K): this talk ($\theta = 0$)

no-go theorem: hints on a derivation

- perturbation series in qubit-oscillator coupling:
  terms of the structure

$$\int_{-\infty}^{\infty} \mathrm{d}t_1 \int_{t_1}^{\infty} \mathrm{d}t_2 \int_{t_2}^{\infty} \mathrm{d}t_3 \ldots \exp\Big[\mathrm{i}\sum_{\ell}\big(\lambda_\ell \Omega t_\ell + \frac{v}{2\hbar}(t_{2\ell}^2 - t_{2\ell-1}^2)\big)\Big]$$

  where $\lambda_\ell = \pm 1$ (from $b^\dagger$ and b)

- substitution to time differences

$$\int_{-\infty}^{\infty} \mathrm{d}t_1 \int_{0}^{\infty} \mathrm{d}\tau_2 \mathrm{d}\tau_3 \ldots$$

- first integral provides $\delta\big(v\sum_{\ell}\tau_\ell + \Omega\sum_{\ell=1}^{2k}\lambda_\ell\big)$

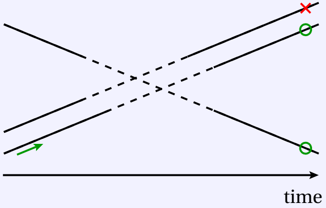
- since all $\tau_\ell \geq 0$ ➔ $\sum_{\ell}^{2k}\lambda_{\ell=1} \leq 0$

- all terms with “<” have vanishing prefactors ➔ $\lambda_\ell = (-1)^\ell$

Sweep a qubit to entangle states and to gauge its environment

- What is a Landau-Zener transition?
- Experiment: circuit QED
- Qubit coupled to a quantum oscillator
- Dissipative Landau-Zener transitions

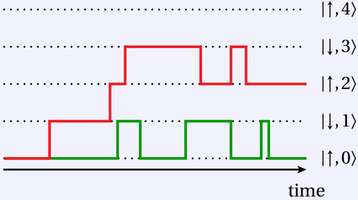
- three-level Landau-Zener problem



- upper level finally never populated
  ➔ "no-go theorem"
  Brundobler & Elser (1993)
  Shytov (2004); Volkov & Ostrovsky (2005); Dobrescu & Sinitsyn (2006)

- generalization to infinitely many levels

  series for $\langle\uparrow, n|U(\infty, -\infty)|\uparrow, 0\rangle$ with perturbation $H_{\text{int}} = \gamma\sigma_x(b^\dagger + b)$



- no contribution
- only contribution: repeated jumps between $|\uparrow, 0\rangle$ and $|\downarrow, 1\rangle$