KICK OFF MEETING: Q-DYNAMO

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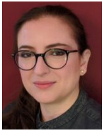
Parma is best known for ...

Parma group

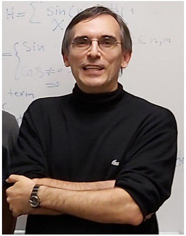
- F. Petiziol (external, TU Berlin)
- I. Saychenko (PhD)
- 2 Postdocs, starting 5/24

Collaborations:

- E. Arimondo & D. Ciampini (Pisa)
- M. Andersen (Otago)
- T. Kirova (Riga)
- M. Sadgrove (Tokyo)
- ...



OUR RESEARCH



My research topics:

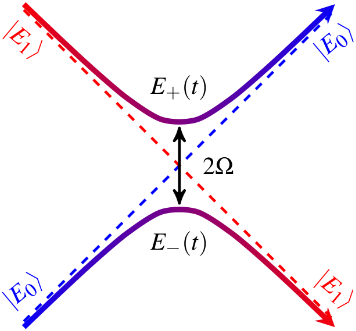
- atomic physics and quantum optics ($\rightarrow$ Floquet driven system)
- Bose-Einstein condensates ($\rightarrow$ experiments in Pisa, Kaiserslautern, Stillwater, Tokyo, Auckland, Otago, ...)
- nonlinear Schrödinger equations ($\rightarrow$ BECs and Cold Dark Matter)
- **quantum control (Q info, state transfer) $\rightarrow$ Q-DYNAMO**

Landau-Zener Hamiltonian

$$H_0(t) = \lambda t \hat{\sigma}_z + \Omega \hat{\sigma}_x$$

Energy levels

$$E_{\pm}(t) = \pm\sqrt{(\lambda t)^2 + \Omega^2}$$



Avoided crossing

Sweeping through avoided crossing **mixes states**

Adiabatic passage

Driving an instantaneous eigenvector slowly realizes **robust** population transfer!

TRANSITIONLESS/COUNTERDIABATIC DRIVING

«[...] Hamiltonians $\hat{H}(t)$, associated with any chosen $\hat{H}_0(t)$, that drive the instantaneous eigenstates of $\hat{H}_0(t)$ exactly.»

J. Phys. A **42**, 365303 (2009)

Michael Berry

Origins of STA:

- Berry, Proc. R. Soc. A 414, 31 (1987)
- STIRAP – Unanyan, Yatsenko, Bergmann, Shore, Opt. Commun. 139, 48 (1997)
- Chemistry – Demirplak, Rice, J. Phys. Chem. A 107, 9937 (2003)
- Guery-Odelin, Ruschhaupt, Kiely, Torrontegui, Martinez-Garaot, Muga, RMP 91, 045001 (2019)

Time-dependent control parameter $\lambda(t)$:

$$H_0(\lambda(t))\,|n(\lambda)\rangle = E_n(\lambda(t))\,|n(\lambda)\rangle$$

Expansion into instantaneous eigenbasis

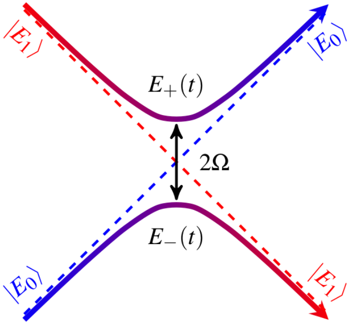
$$|\psi(\lambda(t))\rangle = \sum_n a_n(t)\,|n(\lambda(t))\rangle$$

$$\frac{d}{dt}a_n = -\frac{i}{\hbar}\left(E_n - i\hbar\dot{\lambda}\,\langle n|\,\frac{\partial n}{\partial \lambda}\rangle\right)a_n - \dot{\lambda}\sum_{m\neq n}\frac{\langle m(\lambda(t))|\,\frac{\partial H_0}{\partial \lambda}\,|n(\lambda(t))\rangle}{E_n - E_m}a_m(t)$$

We cancel the red transition part by changing the original Hamiltonian:

$$H(t) = H_0 + i\hbar\sum_{m\neq n}\frac{|m\rangle\,\langle m|\,\partial_t H_0\,|n\rangle\,\langle n|}{E_n - E_m}.$$

Example: LZ qubit



$$H_0(t) = \begin{bmatrix} \lambda(t) & \Omega \\ \Omega & -\lambda(t) \end{bmatrix}$$

$$\Longrightarrow \quad H(t) = H_0 + H_{CD} = \begin{bmatrix} \lambda(t) & \Omega + i\frac{1}{2}\frac{\Omega\ \partial_t \lambda(t)}{\lambda(t)^2+\Omega^2} \\ \Omega - i\frac{1}{2}\frac{\Omega\ \partial_t \lambda(t)}{\lambda(t)^2+\Omega^2} & -\lambda(t) \end{bmatrix}$$

$$\boldsymbol{H}_{\mathrm{eCD}}(\boldsymbol{t}) = X\sin(\omega t)\hat{\sigma}_x + Z\cos(\omega t)\hat{\sigma}_z$$ ①

"Simulate"

$$\boldsymbol{H}_{\mathrm{CD}}(\boldsymbol{t}) = f_{\mathrm{CD}}(t)\hat{\sigma}_y$$

$$\boldsymbol{U}_{\mathrm{eCD}}(\boldsymbol{T}) = e^{-i(\overline{H}^{(0)} + \frac{1}{\omega}\overline{H}^{(1)})T + o(T^3)}$$

$$\overline{H}^{(0)} = 0$$

$$\overline{H}^{(1)} = XZT\hat{\sigma}_y$$ ②

Match

$$\boldsymbol{U}_{\mathrm{CD}}(\boldsymbol{T}) \simeq e^{-iTf_{\mathrm{CD}}(t)\hat{\sigma}_y + o(T^3)}$$ ③

Constraints for driving amplitudes

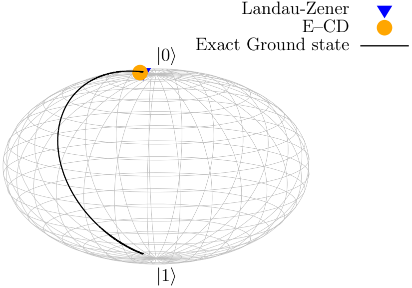
④

$$X(t)Z(t) = \omega f_{\mathrm{CD}}(t)$$

Example case: Assisted LZ sweep

LZ Accelerating Hamiltonian

$$H_{\mathrm{eCD}}(t) = \sqrt{\frac{\omega}{2}\frac{\lambda_0\Omega}{(\lambda_0 t)^2 + \Omega^2}}\,[\sin(\omega t)\sigma_z - \cos(\omega t)\sigma_x]$$



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Perspective

Quantum control by effective counterdiabatic driving

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Abstract – We review a scheme for the systematic design of quantum control protocols based on shortcuts to adiabaticity in few-level quantum systems. The adiabatic dynamics is accelerated by introducing high-frequency modulations in the control Hamiltonian, which mimic a time-dependent counterdiabatic correction. We present a number of applications for the high-fidelity realization of quantum state transfers and quantum gates based on effective counterdiabatic driving, in platforms ranging from superconducting circuits to Rydberg atoms.

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PHYSICAL REVIEW A **99**, 042315 (2019)

Accelerating adiabatic protocols for entangling two qubits in circuit QED

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We introduce a method to speed up adiabatic protocols for creating entanglement between two qubits dispersively coupled to a transmission line, while keeping fidelities high and maintaining robustness to control errors. The method takes genuinely adiabatic sweeps, ranging from a simple Landau-Zener drive to boundary cancellation methods and local adiabatic drivings, and adds fast oscillations to speed up the protocol while canceling unwanted transitions. We compare our protocol with existing adiabatic methods in a state-of-the-art parameter range and show substantial gains. Numerical simulations emphasize that this strategy is efficient also

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SCIENTIFIC REPORTS

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[1] Diparti … Italy

Optimized three-level quantum transfers based on frequency-modulated optical excitations

Francesco Petiziol[1,2*], Ennio Arimondo[3,4], Luigi Giannelli[5], Florian Mintert[6] & Sandro Wimberger[1,2]

The difficulty in combining high fidelity with fast operation times and robustness against sources of noise is the central challenge of most quantum control problems, with immediate implications for

cancellation methods and local adiabatic drivings, and adds fast oscillations to speed up the protocol while canceling unwanted transitions. We compare our protocol with existing adiabatic methods in a state-of-the-art parameter range and show substantial gains. Numerical simulations emphasize that this strategy is efficient also

PHYSICAL REVIEW LETTERS **126,** 250504 (2021)

Quantum Simulation of Three-Body Interactions in Weakly Driven Quantum Systems

Francesco Petiziol,[1,2,*] Mahdi Sameti,[3] Stefano Carretta,[1,2] Sandro Wimberger,[1,4] and Florian Mintert[3]

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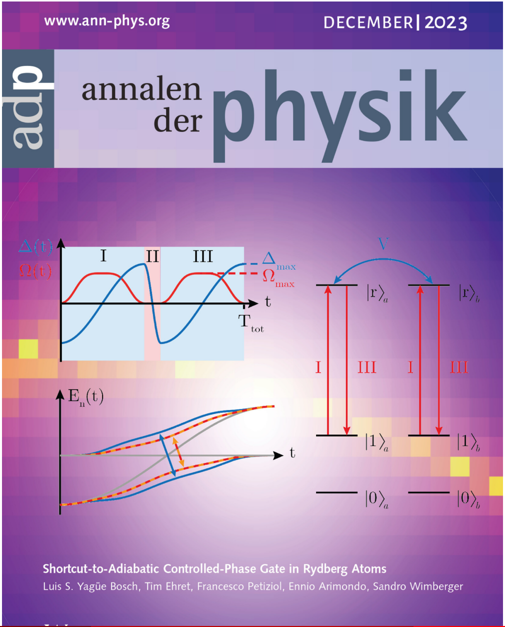
The realization of effective Hamiltonians featuring many-body interactions beyond pairwise coupling would enable the quantum simulation of central models underpinning topological physics and quantum computation. We overcome crucial limitations of perturbative Floquet engineering and discuss the highly accurate realization of a purely three-body Hamiltonian in superconducting circuits and molecular nanomagnets.

Francesco Petiziol[1,2*], Ennio Arimondo[3,4], Luigi Giannelli[5], Florian Mintert[6] & Sandro Wimberger[1,2]

The difficulty in combining high fidelity with fast operation times and robustness against sources of noise is the central challenge of most quantum control problems, with immediate implications for

dependent counterdiabatic correction. We present a number of applications for the high-fidelity realization of quantum state transfers and quantum gates based on effective counterdiabatic driving, in platforms ranging from superconducting circuits to Rydberg atoms.

APPLICATIONS OF EFFECTIVE CD METHOD



Press release and start of Q-Dynamo

UNIVERSITÀ DI PARMA

EU GREEN EUROPEAN ALLIANCE

CHI SIAMO CORSI RICERCA NOI E I

Fisica quantistica: l'Università di Parma nel progetto internazionale Q-DYNAMO

Unico Ateneo italiano con Pisa. Gruppi di ricerca di quattro continenti per la realizzazione di nuovi strumenti per le tecnologie quantistiche

Parma, 28 novembre 2023 - Al Dipartimento di Scienze Matematiche, Fisiche e Informatiche dell'Università di Parma parte un nuovo progetto di ricerca europeo d'ambito quantistico.

Il progetto s'intitola **Q-DYNAMO** (Quantum Dynamic Control of Atomic, Molecular and Optical Processes) ed è parte del programma europeo HORIZON-TMA-MSCA-SE-2022. Oggetto della ricerca è il controllo dei sistemi quantistici alla base dei metodi sviluppati a Parma. Il progetto è guidato da **Teodora Kirova** dell'Università di Riga (Lettonia) e si avvale della collaborazione di gruppi di ricerca di quattro continenti (Germania, Giappone, Italia, Lettonia, Nuova Zelanda e USA). L'Italia è rappresentata dalle Università di Parma e Pisa. Per l'Università di Parma sono coinvolti il docente Sandro Wimberger, che da tempo lavora su questi temi, e il suo gruppo.

Questo progetto europeo, insieme a un altro del gruppo Wimberger afferente al PRIN 2022 e intitolato *Quantum Atomic Mixtures: Droplets, Topological Structures, and Vortices*, punta alla realizzazione di nuovi strumenti per le tecnologie quantistiche. Entrambi rappresentano un'importante occasione di interscambio di idee e persone con istituzioni nazionali, europee ed extraeuropee, conferendo all'Università di Parma un ruolo rilevante nel panorama scientifico e tecnologico internazionale.

THANK YOU VERY MUCH!

- Review of eCD method: Petiziol, Mintert, Wimberger, EPL **145**, 15001 (2024)
- with Pisa: Petiziol, Arimondo, Giannelli, Mintert, Wimberger, Sci. Rep. **10**, 2185 (2020)
- with Pisa: Delvecchio, Petiziol, Arimondo, Wimberger, Phys. Rev. A **105**, 042431 (2022)
- with Pisa: Yague Bosch, Ehret, Petiziol, Arimondo, S. Wimberger, Ann. Phys. **12**, 2300275 (2023)
- with Riga/Pisa: Delvecchio, Kirova, Arimondo, Ciampini, Wimberger, Phys. Rev. A **106**, 052802 (2022)
- with Otago: AOKR: Andersen, Wimberger, Phys. Rev. A **105**, 013322 (2022)
- with Tokyo: nanofibre control of atoms: Sadgrove, Wimberger, Nic Chormaic, Sci. Rep. **6**, 28905 (2016)