Adiabatic dynamics of quantum many-body systems

Oleg Lychkovskiy

Skolkovo Institute of Science and Technology

Steklov Mathematical Institute

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Overview

1. Quantum many-body adiabaticity and orthogonality catastrophe
   - Quantum adiabaticity
   - Orthogonality catastrophe
   - Relation between adiabaticity and orthogonality catastrophe
   - Gap condition and many-body quantum adiabaticity
   - Grover adiabatic search
2. Genuine many-body adiabaticity *vs* thermodynamic adiabaticity
   - Thermodynamic adiabaticity
   - Case study: An impurity particle in a 1D quantum fluid
3. Adiabaticity at a finite temperature
4. Summary and outlook

Quantum Adiabatic Theorem

Quantum Adiabatic Theorem (QAT) – colloquially:

A system evolving under a time-dependent Hamiltonian can be kept arbitrarily close to the Hamiltonian's instantaneous ground state provided that the parameters of the Hamiltonian vary *slowly enough*.

Key question: What is the exact meaning of *"slowly enough"*?

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- Quantum Field Theory
- *etc*

Notations and definitions

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- Simplest case: linear driving, $\lambda(t) = \Gamma t$, Γ being the driving rate. In general, $\Gamma = \partial\lambda/\partial t$.
- Use λ instead of t as the evolution parameter. Schrodinger equation:

$$i\,\Gamma\,\frac{\partial}{\partial\lambda}\Psi_\lambda = \hat{H}_\lambda\,\Psi_\lambda.$$

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- One calls the evolution adiabatic as long as Ψ_λ remains close to Φ_λ, or in other words if the fidelity

$$\mathcal{F}(\lambda) = |\langle \Phi_\lambda | \Psi_\lambda \rangle|^2$$

  is close to one.

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Q1. For a given driving rate Γ, how long the adiabaticity can be maintained with a given accuracy ε?

Q2. How small should the driving rate Γ be for a given target λ and a given accuracy ε?

Orthogonality catastrophe

Orthogonality catastrophe – colloquially:

Given a many-body Hamiltonian $\hat{H}_\lambda$, two ground states corresponding to slightly different λ's can become nearly orthogonal with growing size of the system, N [Anderson, 1967].

Orthogonality catastrophe

Orthogonality catastrophe – rigorously. *Orthogonality overlap* in the leading order in λ:

$$\mathcal{C}(\lambda) \equiv |\langle \Phi_\lambda | \Phi_0 \rangle|^2 = e^{-C_N \lambda^2}.$$

The orthogonality catastrophe takes place whenever $C_N \to \infty$ in the thermodynamic limit (TL), $N \to \infty$. The behavior of C_N is determined by the type of driving and the gap.

Orthogonality catastrophe: scaling

$$\mathcal{C}(\lambda) \equiv |\langle \Phi_\lambda | \Phi_0 \rangle|^2 = e^{-C_N \lambda^2}.$$

	Local driving	**Bulk driving**
gapless systems	$C_N \sim \log N$	$C_N \sim N$
gapped systems	$\lim_{N\to\infty} C_N$ is finite	$C_N \sim N$

Key idea

In a many-body system subject to orthogonality catastrophe

$$\mathcal{F}(\lambda) \simeq \mathcal{C}(\lambda)$$

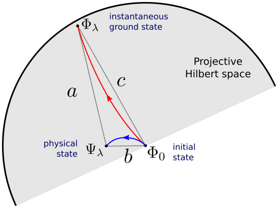
up to times sufficiently long for the adiabaticity to completely break down.

Central result

$$|\mathcal{F}(\lambda) - \mathcal{C}(\lambda)| \leq \mathcal{R}_\lambda$$

$$\mathcal{R}_\lambda \equiv \Gamma^{-1} \int_0^\lambda \sqrt{\langle \hat{H}^2_{\lambda'} \rangle_0 - \langle \hat{H}_{\lambda'} \rangle_0^2} \, d\lambda',$$

where $\langle \cdots \rangle_0 \equiv \langle \Psi_0 | \cdots | \Psi_0 \rangle$.



For $\hat{H}_\lambda = \hat{H}_0 + \lambda \hat{V}$, one gets a simplified $\mathcal{R}_\lambda$:

$$R_\lambda = \lambda^2 \, \delta V_N / (2\Gamma) \quad \text{with} \quad \delta V_N \equiv \sqrt{\langle \hat{V}^2 \rangle_0 - \langle \hat{V} \rangle_0^2}.$$

OL, O. Gamayun, V. Cheianov
PRL 119, 200401 (2017)

Adiabaticity breakdown time (Question 1)

Define the adiabaticity breakdown time t_* and parameter $\lambda_* \equiv \lambda(t_*)$:

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Relation between adiabaticity and orthogonality catastrophe implies

$$\lambda_* = 1/\sqrt{C_N}$$

up to small corrections, as long as $\mathcal{R}(C_N^{-1/2}) \ll 1$. The latter is guaranteed for sufficiently large system since

$$\frac{\delta V_N}{C_N} \to 0 \quad \text{for} \quad N \to \infty.$$

Necessary condition for many-body adiabaticity (Q 2)

If the orthogonality catastrophe is present, the adiabaticity can be maintained for finite systems only as long as $\mathcal{R}(\lambda_*)$ is large enough to make inequality

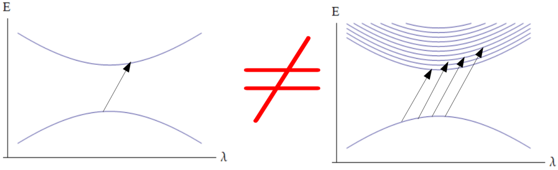
$$|\mathcal{F}(\lambda) - \mathcal{C}(\lambda)| \leq \mathcal{R}_\lambda$$

trivial.

This entails a **necessary adiabatic condition:**

$$\Gamma_N < \frac{\delta V_N}{2C_N} \frac{1}{1 - e^{-1} - \varepsilon}.$$

Adiabaticity and a gap



In a two-level system adiabaticity is governed by the gap (Landau-Zener). The adiabatic condition:

$$\Gamma \ll \Delta E_{\min}.$$

A Landau-Zener-type guess is typically **completely wrong** for bulk driven many-body systems! The adiabatic condition:

$$\Gamma \ll f_N \, \Delta E_{\min} \quad \text{with} \quad \lim_{N\to\infty} f_N = 0.$$

Take-home message

Maintaining adiabaticity in a many-body system is challenging.

Even more challenging than one may assume based on naive considerations employing energy gap.

Application to Grover adiabatic search

Adiabatic quantum computation:

$$H_t = \left(1 - \frac{t}{T}\right) H_0 + \frac{t}{T} H_P$$

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This scaling reproduces the scaling of the explicitly known optimal run time.

OL, Journal of Russian Laser Research 2018

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Genuine many-body adiabaticity is a *sufficient* condition for a plethora of "adiabatic" phenomena (quantized transport, quasi-Bloch oscillations, adiabatic quantum computation *etc*).

But is it really *necessary*?

Thermodynamic adiabaticity

Thermodynamic adiabaticity (see e.g. Polkovnikov, Gritsev, Nature Phys. 2008):

$$\text{energy gaps between levels} \ll \Gamma \ll \text{all intensive energy scales}$$

Thermodynamic *vs* genuine adiabaticity

For gapped spin systems *thermodynamic adiabaticity* is enough for expectation values of local operators to stay close to their ground state values, even if the *genuine adiabaticity* is already broken (Bachmann, De Roeck, Fraas PRL 2017).

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Can it be that the genuine adiabaticity is completely irrelevant in the many-body setting?

This is not always the case!

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We consider dynamics of an impurity in a 1D quantum fluid as an examples.

Mobile impurity in a 1D fluid

A mobile impurity particle in a translation-invariant 1D gas of N fermions

$$\hat{H}_t = \frac{P^2}{2m} + \sum_{n=1}^{N} \frac{p_n^2}{2m} + g_t \sum_{i=1}^{N} \delta(x_i - x)$$

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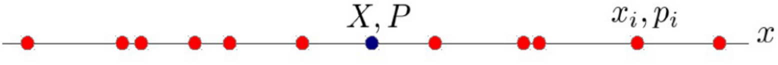

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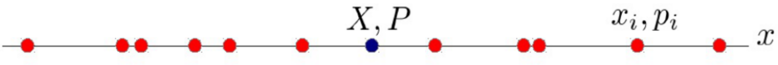

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Coupling is slowly switched on up to a value g:

$$g_t = \Gamma t\, (k_{\mathrm{F}}/m), \qquad t \in [0, \tau], \qquad g_\tau \equiv g$$

Mobile impurity in a 1D fluid

$$\begin{aligned} \hat{H}_t =& \frac{P^2}{2m} + \sum_{n=1}^{N} \frac{p_n^2}{2m} + g_t \sum_{i=1}^{N} \delta(x_i - x) \\ g_t =& \Gamma t, \qquad t \in [0, \tau] \end{aligned} \tag{1}$$

Genuine many-body adiabaticity:

$$\Gamma \ll \Delta E \lesssim E_{\mathrm{F}}/N$$

Thermodynamic adiabaticity:

$$E_{\mathrm{F}}/N \ll \Gamma \ll E_{\mathrm{F}}$$

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Will the local physical observables at $t \gg \tau$ differ?

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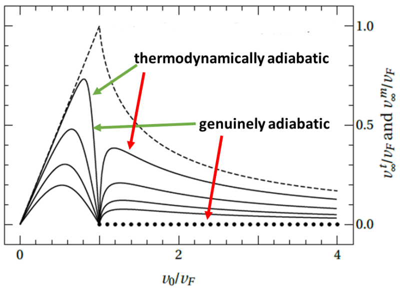

$v_0 < v_{\mathrm{F}}$:

$$v_\infty^{\text{thermodynamic}} = v_\infty^{\text{genuine}}$$

$v_0 > v_{\mathrm{F}}$:

$$v_\infty^{\text{genuine}} = 0$$

$$v_\infty^{\text{thermodynamic}} > 0$$

Gamayun, OL *et al* PRL 2018

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One can enquire about adiabaticity at a finite temperature:

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\begin{aligned}
i\partial_t \rho_t &= [H_t, \rho_t] \\
\rho_0 &= e^{-\beta H_0}/Z_0 \qquad Z_0 \equiv \mathrm{tr} e^{-\beta H_0} \\
\rho_t^\beta &= e^{-\beta H_t}/Z_t \qquad Z_t \equiv \mathrm{tr} e^{-\beta H_t}
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$$||\rho_t - \rho_t^\beta|| = ?$$

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So what happens at a finite temperature?

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Adiabatic theorem at a finite temperature

For $U_t = e^{i\omega t V}$

$$||\rho_t - \rho_t^\beta||_H \leqslant 2\omega\beta\sqrt{\langle V^2\rangle_\beta}\left(1+\sqrt{2}\,(\omega t)\sqrt{\langle V^2\rangle_\beta}\right)$$

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Polynomial system size dependence for global driving ($\langle V^2\rangle_\beta \sim N$)!

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- The adiabaticity breakdown time t_* vanishes in the thermodynamic limit.
- Scaling of t_* with the number of particles, N, is determined by the nature of driving (global or local) and by presense/absense of gapless excitations.
- Contrary to the common belief, whenever driving is of bulk type, even a finite gap is not able to protect adiabaticity in the thermodynamic limit!
- Necessary adiabatic condition for finite systems derived – the most stringent to date, to the best of our knowledge!

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- For others, genuine many-body adiabaticity is strictly necessary.
- The discrimination between the two scenarios is subtle and is currently done on the case-by-case basis. General theoretical understanding is lacking!
- Adiabatic theorem at finite temperature is proven for a particular class of time-dependent Hamiltonians. Energy gaps do not enter!

Thank you for your attention!