Open quantum systems

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Consiglio di Sezione INFN - IS GE41

Outline

1. General infos on IS GE41
2. Open quantum systems
3. Collaborations and publications

IS GE41

- Titolo:
  Fundamental Problems in Quantum Physics
- Sezioni INFN coinvolte:
  Lecce-Cosenza, Milano, Pavia, Trieste, Genova
- Membri unità di Milano:
  Barchielli Alberto (PO, Polimi)
  Gregoratti Matteo (RU, Polimi)
  Smirne Andrea
  (Assegnista Unimi PRIN 2008
  $\rightarrow$ Assegnista Units FP7 FET-OPEN *NANOQUESTFIT*)
  Toigo Alessandro (RTD, Polimi)
  Vacchini Bassano (RU Unimi)
- Progetti collegati:
  COST Action MP1006:
  Fundamental Problems in Quantum Physics
  Futuro in ricerca 2010:
  Semigruppi Quantistici Markoviani e la loro stima empirica

Outline

1. General infos on IS GE41
2. Open quantum systems
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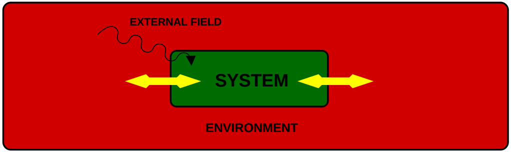
Open quantum systems

- Quantum system interacting with environment
  Quantum optics, condensed matter theory, physical chemistry, quantum measurement, decoherence. . .

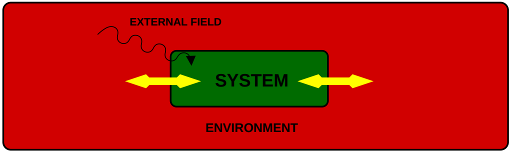


- Physical motivations
  - Perfect isolation of a quantum system is not possible
  - Measurement theory
  - Quantum-to-classical transition and decoherence
  - Quantum information
- Mathematical aspects
  - Irreversible dynamical maps
  - Positive operator-valued measures and instruments
  - Insights from classical probability theory

[Breuer & Petruccione, The Theory of Open Quantum Systems, Oxford 2002]
[Barchielli & Gregoratti, Quantum Trajectories and Measurements in Continuous Time, Springer 2009]

Open quantum systems

- Quantum system interacting with environment



- Bipartite setting $H \in \mathcal{B}(\mathcal{H}_S \otimes \mathcal{H}_E)$ $\rho_{SE} \in \mathcal{T}(\mathcal{H}_S \otimes \mathcal{H}_E)$
  System observables only determined by $\rho_S(t) = \mathrm{Tr}_E\, \rho_{SE}(t)$

$$\frac{d}{dt}\rho_S(t) = -\frac{i}{\hbar}\mathrm{Tr}_E[H, \rho(t)] \qquad \rho_S(0) = \mathrm{Tr}_E\, \rho_{SE}(0)$$

- Role of correlations
  - Initial correlations $\rho_{SE}(0) \neq \rho_S(0) \otimes \rho_E(0)$
    do not allow closed physical reduced dynamics
  - Time evolved correlations $\rho_{SE}(t) \neq \mathrm{Tr}_E\, \rho_{SE}(t) \otimes \mathrm{Tr}_S\, \rho_{SE}(t)$
    allow for memory effects and non-Markovianity

Quantum dynamical map

- Reduced dynamics

$$\begin{array}{ccc} \rho(0) = \rho_S(0) \otimes \rho_E & \xrightarrow{\text{unitary evolution}} & \rho(t) = e^{-\frac{i}{\hbar}Ht}(\rho_S(0) \otimes \rho_E)e^{+\frac{i}{\hbar}Ht} \\ \mathrm{Tr}_E \big\downarrow & & \big\downarrow \mathrm{Tr}_E \\ \rho_S(0) & \xrightarrow{\text{dynamical map}} & \rho_S(t) = \Phi(t)\rho_S(0) \end{array}$$

- Quantum dynamical map

$$\rho_S(0) \mapsto \rho_S(t) = \Phi(t)\rho_S(0) = \mathrm{Tr}_E(e^{-\frac{i}{\hbar}Ht}(\rho_S(0) \otimes \rho_E)e^{+\frac{i}{\hbar}Ht})$$

Completely positive trace preserving map

Dynamical semigroup evolution

- Markov condition
  Separation of system environment time scales
- Semigroup property

$$V(t)V(s) = V(t+s) \qquad t, s \geq 0 \qquad V(t) = \exp(\mathcal{L}t)$$

- Quantum dynamical semigroups
  Quantum Markov process

$$\frac{d}{dt}\rho_S(t) = \mathcal{L}\rho_S(t)$$

$$\mathcal{L}\rho_S(t) = -\frac{i}{\hbar}[H_S + H_{eff}, \rho_S(t)] + \sum_\alpha \gamma_\alpha \left[A_\alpha \rho_S(t) A_\alpha^\dagger - \frac{1}{2}\{A_\alpha^\dagger A_\alpha, \rho_S(t)\}\right]$$

Master equation in Lindblad form

General non-Markovian evolution

- Memory kernel determined by
  $\mathcal{E} \rightarrow$ completely positive trace preserving map
  $\mathcal{F}(t) \rightarrow$ collection of time dependent completely positive trace preserving maps
  $f(t) \rightarrow$ waiting time distribution of renewal process
- Master equation

$$\frac{d}{dt}\rho(t) = \int_0^t d\tau \frac{d}{d(t-\tau)}[f(t-\tau)\mathcal{F}(t-\tau)]\mathcal{E}\rho(\tau) + f(0)\mathcal{E}\rho(t) + \frac{d}{dt}\left[g(t)\mathcal{F}(t)\right]\rho(0)$$

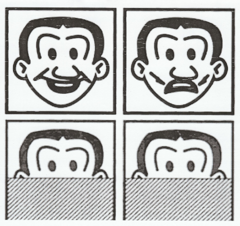
Approaches to obtain general evolution equations

Notion of non-Markovianity

- Non-Markovianity from directionality of information flow

Info flow Info backflow

- Markovian dynamics:
  system irreversibly loses info towards the environment
- Non-Markovian dynamics:
  system partially recovers info from the environment
- Distinguishability of different time evolved states as quantifier of info flow



Distinguishability

- Distinguishability can be measured through the trace distance between system states ρ_1 and ρ_2

$$D(\rho_1, \rho_2) = \frac{1}{2}\|\rho_1 - \rho_2\|_1 = \frac{1}{2}\,\mathrm{Tr}\,|\rho_1 - \rho_2|$$

- Quantum dynamical semigroups monotonic contractions

$$\Phi(s)\Phi(t) = \Phi(t+s) \qquad \forall t, s \geq 0$$
$$D(\rho_1(t+s), \rho_2(t+s)) \leq D(\rho_1(t), \rho_2(t))$$

- Non-Markovian quantum dynamics if

$$\frac{d}{dt}D(\rho_1(t), \rho_2(t)) > 0$$

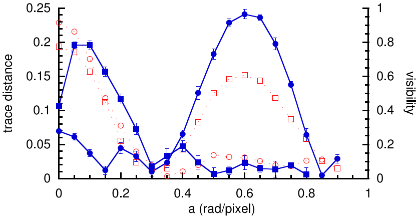
for some pair of initial states $\rho_{1,2}(0)$ and some time $t > 0$

Distinguishability via trace distance

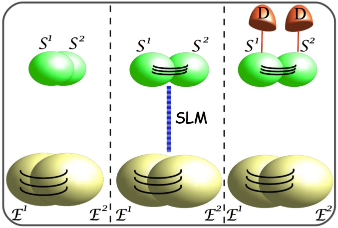
Experimental results

- Bipartite system in quantum optical setting

system $\rightarrow$ polarization degrees of freedom
environment $\rightarrow$ frequency degrees of freedom



Detection of initial correlations



System as environmental probe

Experimental accessibility of trace distance information

Outline

Collaborazioni:

- S. Attal: Université Claude Bernard Lyon 1, Francia
- H.-P. Breuer: University of Freiburg, Germania
- G. Chiribella: Tsinghua University, Cina
- T. Heinosaari, E.-M. Laine, J. Piilo: University of Turku, Finlandia
- K. Hornberger: University of Duisburg-Essen, Germany
- L. Mazzola, M. Paternostro: Queen's University, Ireland
- C. Pellegrini: Université Paul Sabatier, Francia
- F. Petruccione: University of KwaZulu-Natal, Sudafrica
- C. Carmeli, V. Umanità: Università di Genova
- S. Cialdi, M. Paris, R. Martinazzo: Unimi

Selezione pubblicazioni recenti (2008-2013): [Open quantum systems]

- A. Smirne, L.Mazzola, M. Paternostro and B. Vacchini
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- A. Smirne, E.-M. Laine, H.-P. Breuer, J. Piilo, B. Vacchini
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- A. Smirne, D. Brivio, S. Cialdi, B. Vacchini, M. G. A. Paris
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- H.-P. Breuer and B. Vacchini
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- B. Vacchini
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  Lect. Notes Phys. 782 (Springer, Berlin, 2009)
- A. Barchielli, M. Gregoratti, M. Licciardo
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  Int. J. Quantum Information vol. 6 581 (2008)