Quantum-NEST

ETTORE MAJORANA FOUNDATION AND CENTER FOR SCIENTIFIC CULTURE

SUMMER SCHOOL

QUANTUM SCIENCE AND TECHNOLOGY

The goal of the **Quantum-NEST School (Quantum Network for Education and Scientific Training)** is to provide an overview of the most recent and exciting evolutions in the **quantum science and technology** field, and on its most exciting developments. The school offers lectures of high-profile scholars in quantum technology: this will provide the students with a clear vision of the main topics and challenges in the field. It will be also a precious networking opportunity to meet established researchers in the field. It is primarily aimed at **master's and PhD students.**

JUNE 24-28, 2024

FONDAZIONE ETTORE MAJORANA - ERICE, ITALY

INVITED LECTURERS

Angelo Bassi, Univ. of Trieste
Luca Innocenti, Univ. of Palermo
João Manuel Viana Parente Lopes, Univ. of Porto
Mauro Paternostro, Univ. of Palermo
Luca Perfetti, Ecole Polytechnique
Simone Luca Portalupi, Univ. of Stuttgart
Jean-François Roch, Univ. Paris-Saclay
Laurent Sanchez-Palencia, Ecole Polytechnique
Fabio Sciarrino, Sapienza Univ. of Rome

TOPICS

Quantum optics and communication, quantum sensors, quantum materials and out-ot-equilibrium dynamics, cold atoms, quantum information, conceptual foundations of quantum mechanics.

ORGANIZERS

Rinaldo Trotta (Sapienza Univ. of Rome)
Marino Marsi (Univ. Paris-Saclay)
Massimo Palma (Univ. of Palermo)

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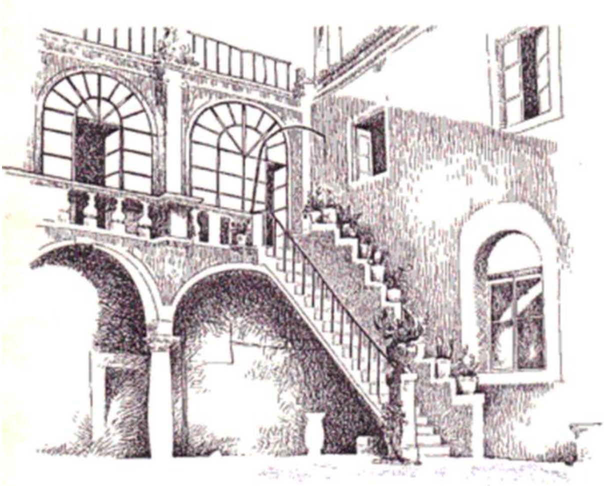
Quantum-NEST Summer School



ETTORE MAJORANA FOUNDATION AND CENTRE FOR SCIENTIFIC CULTURE

INTERNATIONAL SCHOOL OF STATISTICAL PHYSICS
Peter Hänggi and Fabio Marchesoni, Directors

Quantum Network for Education and Scientific Training
(Marino Marsi, Massimo Palma, Rinaldo Trotta, Directors)

Erice, June 24 – June 28, 2024

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PROGRAMME

	June 24th
09:00 - 18:00	Arrival
18:30	Welcome Cocktail at San Rocco

	June 25th
09:00 - 10:00	L. Sanchez-Palencia *"Many-Body Physics in the Era of Quantum Simulation"*
10:00 - 11:00	A.Bassi *"Foundations of Quantum Mechanics"*
11:00 - 11:20	**Coffee break**
11:20 - 12:20	F. Sciarrino *"Integrated photonics for quantum information processing"*
12:20 - 14:00	**Lunch**
14:00 -15:00	A.Bassi *"Foundations of Quantum Mechanics"*
15:00 - 16:00	J-F Roch *"Point defects in diamond as atomic-like systems for quantum technologies"*
16:00 -16:20	**Coffee break**
16:20 - 17:20	J-F Roch *"Point defects in diamond as atomic-like systems for quantum technologies"*

	June 26th
09:00 - 10:00	L. Sanchez-Palencia *“Many-Body Physics in the Era of Quantum Simulation*
10:00 - 11:00	A.Bassi *“Foundations of Quantum Mechanics”*
11:00 - 11:20	**Coffee break**
11:20 - 12:20	L. Perfetti *“Quantum materials: a rich playground of entangled degrees of freedom”*
12:20 - 14:00	**Lunch**
14:00 -15:00	L. Lachaud
15:00 - 16:00	J-F Roch *“Point defects in diamond as atomic-like systems for quantum technologies”*
16:00 -16:20	**Coffee break**
16:20 - 17:20	S. Portalupi *“Epitaxial semiconductor quantum dots: efficient non- classical light sources for quantum technology”*

	June 27th
09:00 - 10:00	L. Sanchez-Palencia *“Many-Body Physics in the Era of Quantum Simulation*
10:00 - 11:00	S. Portalupi *“Epitaxial semiconductor quantum dots: efficient non- classical light sources for quantum technology”*
11:00 - 11:20	**Coffee break**
11:20 - 12:20	L. Perfetti *“Quantum materials: a rich playground of entangled degrees of freedom”*
12:20 - 14:00	**Lunch**
14:00 -15:00	L. Innocenti *“Machine learning for quantum technologies”*
15:00 - 16:00	M. Paternostro *“Sensing gravity-induced entanglement through quantum neuromorphic methods”*
16:00 -16:20	**Coffee break**
16:20 - 17:20	J. Viana Lopes *“Spectral Methods: A route to Quantum Transport”*

	June 28th
09:00 - 10:00	L. Innocenti *“Machine learning for quantum technologies”*
10:00 - 11:00	M. Paternostro *“Sensing gravity-induced entanglement through quantum neuromorphic methods”*
11:00 - 11:20	**Coffee break**
11:20 - 12:20	L. Perfetti *“Quantum materials: a rich playground of entangled degrees of freedom”*
12:20 - 14:00	**Lunch**
14:00 -15:00	**Excursion to Selinunte**
15:00 - 16:00	
16:00 -16:20	
16:20 - 17:20	

SPEAKERS & LECTURES

L. Sanchez-Palencia, CPHT, CNRS, Ecole Polytechnique, IP Paris,
"Many-Body Physics in the Era of Quantum Simulation"

A. Bassi, University of Trieste / INFN
"Foundations of Quantum Mechanics"

F. Sciarrino, Sapienza Università di Roma
"Integrated photonics for quantum information processing"

J-F. Roch, ENS Paris-Saclay & Institut Universitaire de France
"Point defects in diamond as atomic-like systems for quantum technologies"

L. Perfetti, Laboratoire des Solides Irradiés, CEA/DRF/lRAMIS, Ecole Polytechnique / CNRS / Institut Polytechnique de Paris
"Quantum materials: a rich playground of entangled degrees of freedom"

S. Portalupi, *Institut für Halbleiteroptik und Funktionelle Grenzflächen, Center for Integrated Quantum Science and Technology (IQST) and SCoPE, University of Stuttgart*
"Epitaxial semiconductor quantum dots: efficient non- classical light sources for quantum technology"

L. Innocenti, *Università degli Studi di Palermo, Dipartimento di Fisica e Chimica - Emilio Segrè*
"Machine learning for quantum technologies"

M. Paternostro, Quantum Theory Group, Department of Physics and Chemistry E. Segrè, University of Palermo / School of Mathematics and Physics, Queen's University Belfast
"Sensing gravity-induced entanglement through quantum neuromorphic methods"

J. Viana Lopes, *Centro de Física das Universidades do Minho e do Porto / Laboratório de Física para Materiais e Tecnologias Emergentes LaPMET, University of Porto*
"Spectral Methods: A route to Quantum Transport"

Many-Body Physics in the Era of Quantum Simulation

Laurent Sanchez-Palencia
CPHT, CNRS, Ecole Polytechnique, IP Paris, F-91128 Palaiseau, France

The many-body problem is one of the most challenging in physics, with a broad range of applications, from quantum materials, superconductivity, and magnetism to stellar objects. The aim here is to understand the behaviour of systems made up of a huge number of interacting particles, giving rise to emergent phenomena such as phase transitions, with no equivalent in their counterparts made up of a small number of particles. In the quantum domain, the problem is hampered by the exponentially growth of the Hilbert space, and the solution relies on educated approximations, which have widely proved fruitful. In this context, the development of quantum simulators allows us to shed new light on this problem.

This series of lectures provides an introduction to the many-body problem and its connection to quantum simulation. After reviewing the scope of the subject, we will give a brief introduction to the second quantization formalism and the construction of many-body models. We will then review some of the theoretical approaches developed to solve them and the open questions. Finally, we will discuss how quantum simulation opens up unprecedented perspectives in this context.

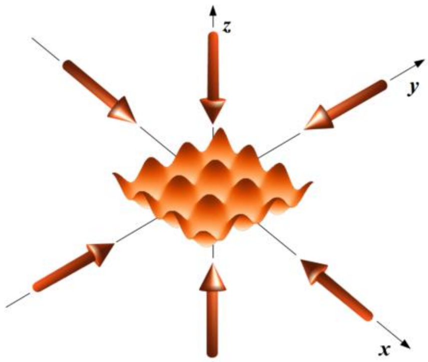

Figure 1: Optical lattice for ultracold atoms. A quasi-perfect periodic potential is realized from the interference pattern of pairs of counter-propagating laser beams. At very low temperatures, the atoms are the anti-nodes (sites) of the lattice. They can hop from one site to another by tunnel coupling and interact at short distances, hence simulating the celebrated Hubbard model.

Foundations of Quantum Mechanics

Angelo Bassi
University of Trieste, Strada Costiera 11, 34151 Trieste
INFN, Trieste Section, Via Valerio 2, 34127 Trieste

I will present some of the main topics in the Foundations of Quantum Mechanics, specifically:

1. The role of operators in Quantum Mechanics: Why do self-adjoint operators represent physical observable quantities? We will derive the operator formalism by analyzing how experiments on quantum systems work.
2. Completeness and incompleteness: Does the wave function represent the ultimate description of Nature, or is there more to it? We will present Bohmian Mechanics and the future research directions it suggests.
3. Is the collapse of the wave function real? If so, then we must modify the Schrödinger equation. We will introduce models of spontaneous wave function collapse and their experimental testability.

The goal of the lectures is to show that Quantum Mechanics calls for a deeper level of explanation, which will ultimately lead to a new theory with far-reaching experimental consequences.

Suggested literature:
[1] Detlef Duerr and Dustin Lazarovici: "Understanding Quantum Mechanics: The World According to Modern Quantum Foundations", Springer (2020).
[2] Travis Norsen: "Foundations of Quantum Mechanics: An Exploration of the Physical Meaning of Quantum Theory", Springer (2017).
[3] Roderich Tumulka: "Foundations of Quantum Mechanics" Springer (2022).

Integrated photonics for quantum information processing

Fabio Sciarrino
Sapienza Università di Roma, Dipartimento di Fisica, P.le Aldo Moro 2, 00181 Roma

Photonic quantum technologies represent a promising platform for several applications, ranging from long-distance communications to the simulation of complex phenomena. Indeed, the advantages offered by single photons do make them the candidate of choice for carrying quantum information in a broad variety of areas with a versatile approach. Furthermore, recent technological advances are now enabling first concrete applications of photonic quantum information processing. The goal of this lecture t is to provide the audience with an overview of the state of the art in this active field, with a due balance between theoretical, experimental and technological results.

[1] E Pelucchi et al., "The potential and global outlook of integrated photonics for quantum technologies", Nature Reviews Physics 4 (3), 194-208 (2022).

[2] J. Wang, F. Sciarrino, A. Laing, and M.G. Thompson, "Integrated photonic quantum technologies", Nature Photonics 14 (5), 273-284 (2020).

[3] F. Flamini, N. Spagnolo, and F. Sciarrino, "Photonic quantum information processing: a review", Rep. Progr. Phys. 82, 016001 (2019).

[4] D.J. Brod, E. F. Galvao, A. Crespi, R. Osellame, N. Spagnolo, and F. Sciarrino, "Photonic implementation of Boson Sampling: a review", Advanced Photonics 1, 034001 (20

Point defects in diamond as atomic-like systems for quantum technologies

Jean-François ROCH
ENS Paris-Saclay & Institut Universitaire de France

It is often said that crystals are like people: it is often their flaws that make them interesting... For example, the color of diamond gems is linked to the existence of impurities within the crystal. These defects give the material specific optical, electrical and magnetic properties.

Th lectures will describe how these defects behave like artificial atoms nestled within the diamond crystalline matrix. We will apply first-principles quantum mechanics to the most studied point defect in diamond, the nitrogen-vacancy center, in order to construct its energy levels and understand its luminescence and spin properties.

We will then describe techniques that have been developed to fabricate the NV center and address it down to the individual level.

We will finally describe how the unique quantum properties of the NV center can be used for quantum sensing, leading today to a myriad of applications.

Quantum materials: a rich playground of entangled degrees of freedom

L. Perfetti
1. Laboratoire des Solides Irradiés, CEA/DRF/lRAMIS, Ecole Polytechnique, CNRS, Institut Polytechnique de Paris, F-91128 Palaiseau, France

Quantum materials are a class of materials where the entanglement between quantum degrees of freedom plays a crucial role in determining their properties. They have potential applications in advanced technologies such as quantum computing, high-performance electronics and new sensing devices. In this talk I will primarily discuss light matter interaction in several of these systems, as surface states with strong spin-orbit coupling, which are the subject of current research to convert spin to charge current or reverse the magnetization by current pulses. We will see that some of these states are also protected by topological invariants and take the form of spin-polarized Dirac cones. In a Floquet regime, intense and periodic electromagnetic waves can be used to induce photonic dressing of electronic bands leading to replicas that can couple to each other. The second class of materials we will explore are 2D semiconductors supporting strongly bounded excitons in valleys at high symmetry points. Such electron-hole pairs can be spatially separated in heterostructures with Moirée patterns and can provide an ideal platform for exciton condensation. Finally, I will discuss the interaction between charge order and Coulomb repulsion in a transition metal dichalcogenide showing interesting memristor behavior and chiral properties. The photoexcitation of this compound leads to a coherent motion of the charge order parameter and the ultrafast collapse of the electronic gap.

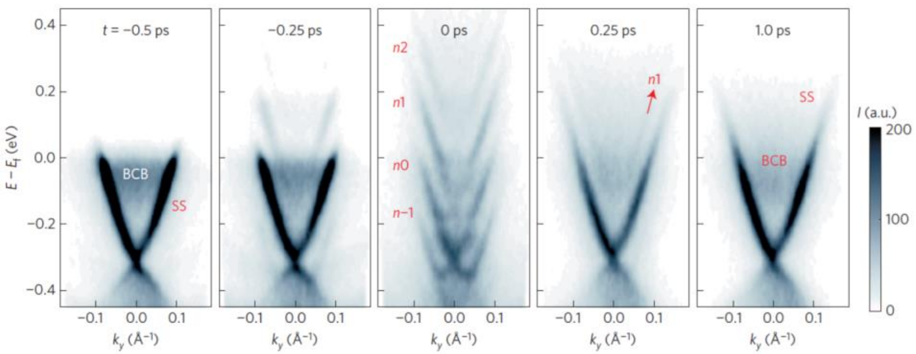

Figure 1: Example of Floquet replica generated by photon dressing some topological surface states.

Epitaxial semiconductor quantum dots: efficient non- classical light sources for quantum technology

Simone L. Portalupi
Institut für Halbleiteroptik und Funktionelle Grenzflächen, Center for Integrated Quantum Science and Technology (IQST) and SCoPE, University of Stuttgart, 70569 Stuttgart, Germany

Quantum technology implementations are currently subject of intense research worldwide. When photonic realizations are targeted, efficient sources of non-classical light (from single to entangled photons) are required.

In this lecture, we will discuss the fundamental properties of non-classical light emission that can be achieved employing semiconductor nanostructures. Together with basics of quantum optics, we will discuss growth and fabrication of epitaxial quantum dots, their physics, and optical and quantum optical properties.

Well-developed nanostructures realized on the gallium arsenide platform will be in the main focus. Experimental results will be discussed, in particular regarding the realization of light sources for on-chip quantum photonics as well as for long distance implementations. The latter will focus on various approaches to reach emission within telecommunication bands and quantum technology implementations outside a controlled lab environment.

[1] *P. Michler and S. L. Portalupi, Semiconductor Quantum Light Sources:Fundamentals, Technologies and Devices, De Gruyter 2024*

Machine learning for quantum technologies

Luca Innocenti
1. Università degli Studi di Palermo, Dipartimento di Fisica e Chimica - Emilio Segrè, via Archirafi 36, I-90123 Palermo, Italy

The marriage of machine learning and quantum information theory and quantum technologies is a field that keeps attracting a lot of interest for both its practical promises and the many open theoretical challenges it presents.

In these lectures, we will provide a brief overview of quantum machine learning. More specifically, we will show how to apply classical machine learning to solve problems faced in quantum information theory, and provide an introduction to quantum-enhanced machine learning, and how it differs from its classical counterpart.

As illustratory examples, we will focus on applications of neural networks to classical experimental quantum optical data, and on the theory and applications of quantum reservoir computing.

[1] Innocenti, Luca, et al. "Potential and limitations of quantum extreme learning machines." Communications Physics 6.1 (2023): 118.
[2] Giordani, Taira, et al. "Machine learning-based classification of vector vortex beams." Physical review letters 124.16 (2020): 160401.

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Sensing gravity-induced entanglement through quantum neuromorphic methods

Mauro Paternostro

1. *Quantum Theory Group, Department of Physics and Chemistry E. Segrè, University of Palermo, via Archirafi 36, I-90123 Palermo, Italy*

2. *School of Mathematics and Physics, Queen's University Belfast, BT7 1NN UK*

The detection of entanglement provides a definitive proof of quantumness. Its ascertainment might be challenging for hot or largw objects, where entanglement is typically weak.

I will discuss a platform for measuring entanglement by connecting the objects of interest to an uncontrolled quantum network, whose emission (readout) is trained to learn and sense the entanglement of the former.

First, I will demonstrate the platform and its features with generic quantum systems. As the network effectively learns to recognise quantum states, it is possible to sense the amount of entanglement after training with only non-entangled states. Furthermore, by taking into account measurement errors, I demonstrate entanglement sensing with precision that scales beyond the standard quantum limit and outperforms measurements performed directly on the objects.

Finally, I will utilise such platform for sensing gravity-induced entanglement between two masses and predict an improvement of two orders of magnitude in the precision of entanglement estimation compared to existing techniques.

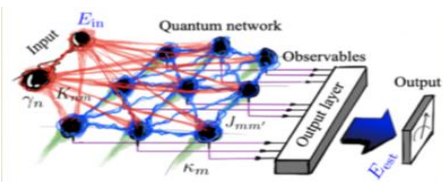

Figure 1: Quantum network for entanglement sensing. The approach can be deployed to detect gravity-induced entanglement

Spectral Methods: A route to Quantum Transport

João M. Viana P. Lopes,
1. Centro de Física das Universidades do Minho e do Porto (CF-UM-UP) and Laboratório de Física para Materiais e Tecnologias Emergentes LaPMET, Departamento de Física e Astronomia e University of Porto, 4169-007 Porto, Portugal

Charge transport in disordered two-dimensional (2D) systems showcases myriad unique phenomenologies that highlight different aspects of the underlying quantum dynamics. Electrons in such systems undergo a crossover from ballistic propagation to Anderson localisation, contingent on the system's effective coherence length. A diffusive crossover between the extended and localised phases lies in the fact that the charge conductivity is properly defined.
The numerical observation of diffusive regime has remained elusive because it requires fully coherent transport to be simulated in systems whose dimensions are sufficiently large to separate the mean-free path and localisation length scales.
Spectral methods have proven highly accurate in computing electronic and quantum transport properties in disordered systems [1,2]. We employed a novel linear scaling time-resolved approach [3], to derive the DC-transport characteristics and observe the three expected 2D transport regimes: ballistic, diffusive, and localised.

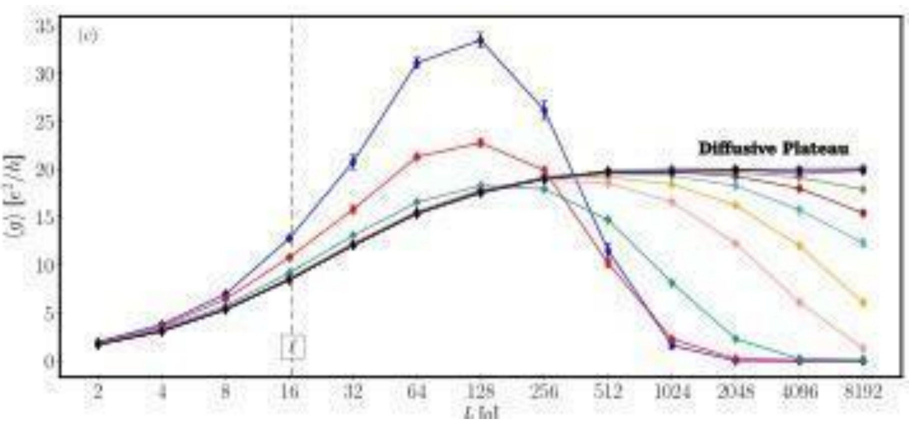

Figure 1: Disordered-averaged scaled conductance as a function of the mesoscopic devices geometries, for a fixed Anderson disorder strength, W = 0.9w..

[1] S. M. João and J. M. Viana Parente Lopes, Basis-independent spectral methods for non-linear optical response in arbitrary tight-binding models, J. Phys.: Condens. Matt. 32(12), 125901 (2019), doi:10.1088/1361-648X/ab59ec.

[2] S. M. João, M. Anđelković, L. Covaci, T. G. Rappoport, J. M. Viana Parente Lopes and A. Ferreira, KITE: high-performance accurate modelling of electronic structure and response functions of large molecules, disordered crystals and heterostructures, R. Soc. Open Sci. 7(2), 191809 (2020), doi:10.1098/rsos.191809.

[3] J. P. Santos Pires, B. Amorim and J. M. Viana Parente Lopes, Landauer transport as a quasisteady state on finite chains under unitary quantum dynamics, Phys. Rev. B 101(10), 104203 (2020), doi:10.1103/PhysRevB.101.104203.