Ultrafast control of quantum phases of matter (lab Q4Q)

The holy grail of controlling materials' properties on sub-picosecond timescales led to a large number of experiments exploring phase transformations photo-induced by ultrashort light pulses. The basic principle of these experiments is to drive the phase transformation in a material by means of ultrashort light pulses. The most commonly explored schemes are based on the sudden photo-injection of an excess of high-energy electronic excitations by ultrashort light pulses eventually leading to photo-induced-phase-transitions. Under the conditions of short dephasing times (1-10fs) and of photo-excitation within time windows shorter than the characteristic times of the relaxation processes in the system, ultrashort light pulses act merely as an impulsive injector of a large number of excitations. This drives matter into regimes which are characterized by a non-thermal "incoherent" energy distribution between electrons, ions, and spins.

The major emerging limitation of this approach, hampering bi-directional optical control, lies in the fact that while the optical switch between different phases can be driven within picoseconds, the recovery is generally limited to much longer times determined by slower incoherent relaxation processes that are ruled by the thermodynamics of the sample.

To overcome this limitation, an important advance came from the implementation of excitation schemes allowing for resonant excitation of low energy degrees of freedom in solids such as vibrations, magnetic and electronic excitations. In contrast to the "incoherent" phase transitions induced by high-photon energy pulses, the phase transitions triggered by coherent long-wavelength pulses are directly due to the large-amplitude low-frequency coherent excitation of the low energy modes and not related to hot-carrier injection. This means that thermal relaxation processes are no longer an intrinsic limitation for coherently controlled changes of macroscopic material properties and bi-directional changes at rates exceeding the thermodynamic restrictions become conceivable.

In spite of the infancy of this approach, our and others recent disclose a largely unexplored regime of physics where strong electromagnetic fields can be used to "beat" thermal disorder and possibly make quantum coherence viable at ambient conditions.

Major questions are open:

- ✓ What is the mechanism leading to the dynamical formation of quantum coherent matter phases at high temperature?
- ✓ Is the field "cooling" fluctuations in the material or is it rather increasing the stability of quantum coherent phases with respect to thermal fluctuations?
- ✓ What is the role played by the quantum state of the photo-excited low energy mode? Is it really a quasi-classical large amplitude coherent state or are non-classical features, such as squeezing and superposition, the key to unlock the onset of quantum coherent electronic states?
- ✓ To what extent can we exploit in realistic devices the mutual feedback between electromagnetic field and quantum coherent matter phases?

The major limitation to our understanding and exploitation of complex materials is the lack of a protocol to access the role played by the quantum state of low energy degrees of freedom in determining macroscopic material properties. At best we can access the characteristic population dynamics of low energy bosons but to the best of my knowledge, no direct measurement of the quantum state of low energy modes is possible to date.

In order to bridge this gap in the last few years we have been focusing on the idea that it may be possible to map directly the quantum state of low energy modes into the quantum state of the light pulses used to interrogate the dynamical response of the material. In appropriate scattering conditions, we have recently shown that fluctuation of the atomic position may be proportional to photon number fluctuations which can be measured in repeated stroboscopic pump&probe experiments in shot noise limited condition. The basic idea leading my future research is to understand how light-matter interactions can map the fluctuations of intrinsic material properties onto fluctuation of ultrashort light pulses which can be measured through a time resolved reconstruction of the quantum state of ultrashort probe pulses.

- ✓ To what extent time-dependent fluctuation of the low energy material degrees of freedom are mapped by light-matter interaction into statistical properties of light pulses?
- ✓ To what extent we can access non-classical features of the quantum states of low energy degrees of freedom?
- ✓ To what extent fluctuations of the low energy modes (vibrational, magnetic and electronic) determine macroscopic material functionalities?

The PhD project will be embedded in this research program which is the focus of the Q4Q labs at the University of Trieste and Sinctrotrone Trieste S.c.p.a. and will follows two main directions:

i) *Exploiting long wavelength ultrashort light pulses to coherently control material functionalities*

ii) *Exploiting statistical properties, such as photon number fluctuations and multimode correlations in optical pulses in time domain experiments as a new spectroscopic mean The combination of non-linear techniques and quantum state reconstruction will provide richer statistical information than standard linear and non-linear optical spectroscopies and will potentially uncover with unprecedented detail the time evolution of transient states of matter.*

The research proposed will give the student the opportunity to build a research profile recognized across the communities of condensed matter, ultrafast physics and quantum information. The successful student will acquire a profound expertise in non-linear optics, non-equilibrium physics, quantum information techniques for the measurements of statistical properties of light as well as material science and quantum matter properties such as superconductivity.

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Fausti's main publications and ongoing research projects:

Nature Physics, 17, pages368–373(2021)*
Optics Letters, vol. 45, Issue 13, pp. 3498-3501 (2020)*
PNAS 116 (12) 5383-5386 (2019)*
Physical Review Letters 122, 067002 (2019) *
Physical Review Letters 119 (18), 187403 (2017)*
Nature communications 6, 4, 2015*
Nature communications 5, 18, 2014*
Nature materials 12 (10), 882-886, 46, 2013
Nature communications 4, 82, 2013*
Nature materials 12 (6), 535-541, 34, 2013
Nature Photonics 5 (8), 485-488, 58, 2011
Science 331 (6014), 189, 273, 2011*

-ERC Starting Grant, "INhomogenieties and fluctuations in quantum CohErent matter Phases by ultrafast optical Tomography (INCEPT)"

- PRIN Collaborative Project, "Excitonic insulator in two-dimensional long-range interacting systems (EXC-INS)"

- ERC Proof of Concept, "Covariance Based Raman spectroscopy (COBRAS)"