Institute of Physique of Rennes
Light and Matter Departement

TITLE : Ultrafast phase transitions generated by photoinduced strain waves

Supervision :
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Scientific background

Phase transitions can be controlled either at equilibrium by changing temperature or pressure or by impulsive control parameters like optical, THz or electrical pulse [1, 2, 3]. In these dynamical cases, not only the initial effects of the control parameter, say electronic excitation for optical pulse, ultrafast and local electric field for THz one generates the transition. Indeed, elastic effects are also involved through the propagation of strains in the material [1]. The impulsive characteristic of the driving pulse creates a local deformation of the crystal lattice, which moves atoms, modifies mutual interactions and can drive fast or ultrafast phase transitions. Metastable states with different physical properties can appear and generate the phase transition. And so, the implication of these elastic effects presents a universal character and should allow to better understand non-equilibrium transitions, which are less elucidated than those at equilibrium.

Project

The thesis aims to highlight the role of photoinduced elastic waves in a non-equilibrium transition. By deforming the crystal lattice, these waves are able to act on the interactions between atoms and to switch the material into a state with properties different from the initial state. In this project, we want to determine the microscopic conditions allowing to induce a transition. For example, we want to determine which atomic displacements are necessary in terms of direction or amplitude but also in term of necessary duration of the deformation to cause the transformation, whether transient or permanent.

We will be particularly interested in insulator-metal transitions in materials exhibiting strong electronic correlations. In this type of materials, Coulomb interactions between electrons can no longer be taken into account by a simple mean field approximation, as it is the case in band theory. In particular, electronic correlations can lead to a “Mott insulator” state, in complete contradiction with the band theory that predicts a metal. At equilibrium, it is possible to control the transition from this insulating state to a metallic state by applying pressure. These systems are therefore materials of great interest for studies where a microscopic lattice deformation is propagated to induce the transition.

Methods

The experiments will be mainly time-resolved pump-probe experiments carried out on our femtosecond laser facility. To study only the effect of dynamic deformation, it is necessary to directly control the parameters of the strain wave. We have set up an experiment able to optically generate one-dimensional elastic waves whose amplitude can be controlled beyond the optical damage thresholds of materials through gradual amplification of the strain wave (see figure 1). This system will be integrated into a time-resolved pump-probe experiment where the induced phenomenon is probed by a second laser beam outside the optical irradiation zone. This way will make it possible to observe the dynamics of the transition induced specifically by the strain wave. The transformation will be probed by optical beams up to infrared to be able to detect gap closing which can be as small as a few hundred meV in the correlated materials.

Beam time on large instruments will be request to implement an acoustic pump-X-probe experiment in order to characterize, by X-ray diffraction, the movements at the atomic scale during the transition. These measurements can be compared to measurements at equilibrium under pressure and *ab initio* calculations can be carried out to deepen the microscopic vision of the phenomenon.

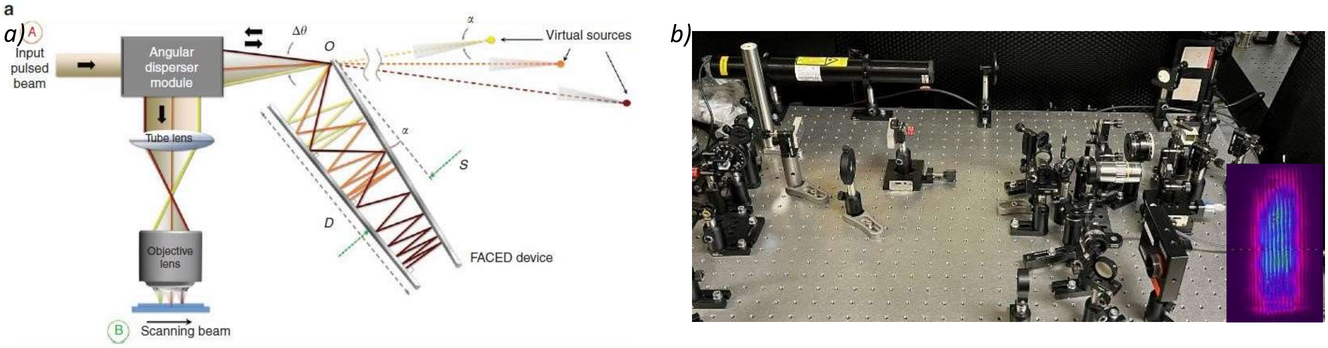

Figure 1: a) Experimental set-up showing the pair of tilted mirrors whose function is to divide the incoming beam into multiple sections amplifying the strain wave at different times during its propagation [5]. b) Transformation of the initial beam after the two mirrors [5].

Supervision

Supervision will associate 3 supervisors: Marina Servol, thesis advisor, will provide her knowledge in terms of non-equilibrium phase transitions and daily supervision at the experimental and data analysis level. JeanChristophe Sangleboeuf, thesis co-advisor, will contribute by his skills in understanding the response of materials to strain waves. Vinh Ta-Phuoc will provide his expertise to guide the choice of materials and will be able to support the PhD student on equilibrium pressure measurements. He will also be able to carry out calculations of optical properties under pressure using DFT calculations.

Environment

The thesis work will take place within the Materials and Light department of the Institute of Physics of Rennes. This department includes approximately 10 permanent and 7 non-permanent staff. Local experimental facilities include two diffractometers and several amplified femtosecond laser equipments, much of them associated with parametric optical amplifiers. The team has very strong links with major large facilities like ESRF and conducts regularly experiments there. The department is also a collaborator of the IRL (International Research Laboratory) DYNACOM between the University of Rennes and the University of Tokyo.

Skills

The candidate must have good knowledge of solid state physics and be motivated to carry out experiments on optical assemblies in free space. He will also need knowledge in X-ray diffraction and be ready to work in a complex environment including large instruments. Knowledge of programming, particularly in Python, will be appreciated.

References:

[1] R. Bertoni et al, Nat. Mat. 15 (6), pp. 606-610 (2016)
[2] G. Huitric et al. Faraday Discuss, 237, 389 (2022)
[3] F. Tesler et al, PRA, 10, 054001 (2018)
[4] B. J. Demaske et al., PRB 87, 054109 (2013)
[5] J-L. Wu et al., Light: Science & Applications 6, 16196 (2017)