PhD Proposal

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Title: Exploring the physics of 2D materials excitations using relativistic electrons

Two dimensional materials have attracted great interest since the reproducible production of graphene. An intense search for new materials and properties has issued many results, including the observation of unconventional superconductivity in graphene twisted bilayers [Cao et al., Nature, 556, 43 (2018)]. Among the large family of possible atomically thin materials, transition metal dichalcogenides (TMDs), such as MoS_2 and WSe_2, have attracted the attention of the community due their visible range bandgap and large spin-orbit coupling. These in combination to the lack of inversion symmetry of their crystal structure lead to spin-valley degrees of freedom which can be manipulated by circularly polarized photons [Xiao et al. Phys. Rev. Lett. 108 196802 (2012)]. Finally, the reduce electromagnetic screening due to their intrinsic 2D nature significantly increases the binding energy of excitons. Therefore the physics usually only accessible at very low temperatures is stable at higher temperature, even up to 300 K.

A key issue in these materials is the production of devices with reproducible features. Large part of the difficulty stems from their 2D nature: surface contaminants modify their local response; bending create strain that changes excitations energies; a few missing atoms completely disrupts their electronic structure. These evident difficulties are actually benefits, as they would allow fine control over the material, if one is capable of generating them in a controlled manner. This means that understanding the material physics at the nanometer to atomic scales is necessary. Standard optical spectroscopies cannot provide information at these reduced scales.

Electron spectroscopies can probe the optical response of matter down to the nanoscale. We can mention, for example, in our group at the LPS the three-dimensional and vector mapping of phonon modes on the surface of nanoparticles [Li et al., Science 371 1364 (2021)], the demonstration of strong plasmon-phonon coupling at the nanoscale [Tizei et al., Nano Letters, 20, 2973 (2020)], the visualization of light emission from hybride Perovskyte nanoparticles [Hou et al., Science 374 6567 (2021)] and the understanding of whispering gallery cavity modes in spheres [Auad et al. Nano Lett. 22 319 (2022)]. For 2D materials these spectroscopies have proven to be excellent probes for excitons, trions (charged excitons), and localized excitations in these materials [Tizei et al., Phys. Rev. Lett. 114 107601 (2015), Bonnet et al., Nano Lett. 21 10178 (2021), Shao et al. ArXiv2202.04483 (2022)]. They can be coupled to electron microscopy techniques (imaging and diffraction) and other spectroscopies to have a complete picture of the materials at the atomic and nano scales. However, a large penalty still exists for electron spectroscopies: the electron intrinsic angular momentum (spin) does not couple to these excitations as the intrinsic angular momentum of a photon does. Therefore, electrons are naturally blind to the distinct spin-valley states, which are easily accessible for photons.

In this thesis project, we will explore, experimentally and theoretically, the possibility accessing these states using purely electron beams. The idea is based on the generation of electron beam carrying angular momentum using electron phase shaping, as demonstrated in 2010 [Verbeeck et al. Nature, 467 301 (2010)]. Spectroscopy with phase shaped beams [Guzzinati et al. 8 14999 (2017)], and proper final state selection [Lourenço-Martins et al., Nat. Phys. 17 598 (2021)] might allow one to probe these state using only electron beams.

We will first study the physics of shaped electron beam coupling to materials in general, including 2D materials. In parallel, we will study electron spectroscopy and perform simple experiment to aquaint the PhD candidate with the experimental techniques (electron energy loss spectroscopy, cathodoluminescence, imaging and diffraction). Finally, we will use phase shaped beams to probe spin-valley states in TMD monolayers.

The project is inserted in the framework o the eBEAM European project. The PhD project will revolve around an unique experimental setup, the ChromaTEM microscope located at the LPS (CNRS/Université Paris-Saclay).

The project is aimed at curious students having an interest in experimental physics, the development of new experimental methods and the understanding of new physical concepts in a booming field of research.