Course on Novel Functionalities in Complex Materials

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In recent years, new topics have emerged to the forefront of condensed matter physics, all of which are strongly tied to advances in materials fabrication: topological materials and multifunctional electronic states in the two-dimensional (2D) limit. The interplay of Coulomb interactions, disorder and crystal structure leads to the formation of novel quantum collective states.

Our course proposes to explore this physics introducing select theoretical tools and experimental techniques allowing one to study 2D electronic states in the presence of strong correlations (Mott), disorder and topology.

There will be eight lectures, one hands-on computer session devoted to the DMFT study of a Mott system and one recitation (TD) on 2D spin-orbit interactions (central to topology and unconventional spin effects).

Highlights:

- Mott transition
- Oxides and oxide interfaces
- Angle-resolved photoemission spectroscopy
- Experimental electronic structure of correlated-electron systems
- Effects of many-body interactions
- Effects of 2D and 1D confinement

Lectures:

1) General introduction to functional materials
   - Introduction to Functional Materials
   - Why functional materials do matter.
   - Transition metal oxides are the Lego bricks of functional materials.
   - Competition leads to versatility.

2) Introduction to strongly correlated electronic systems and the Mott transition

   - Examples.
   - Local versus extended electron interactions.
   - Hubbard model.
   - Interplay between interactions and correlations: Luttinger liquid physics.
   - Green's functions.
   - Mott-Hubbard transition in transition metal oxides.

3) Oxyde heterostructures (I): transport properties

- Metal-Insulator transition at the interface between two large band insulators.
- Weak localization effects
- Rashba spin-orbit scattering
- Berezinskii-Kosterlitz-Thouless versus BCS superconducting transition at the interface.
- Superconductor-insulator quantum critical point.

4) Oxyde heterostructures (II): band structure and topological effects

   - Confinement and band inversion in the presence of spin-orbit
   - Sub-bands in a triangular confining potential well.
   - Topological bands; consequences for the normal and superconducting states.

5) Measuring the electronic structure of materials (I): Introduction to ARPES

   - Photoemission and Angle-Resolved PhotoEmission Spectroscopy (ARPES)
   - Experimental aspects: instrumentation and implementation
   - The photoemission process: independent electrons
   - Band mapping with light

6) Measuring the electronic structure of materials (II) : Many-body effects

   - The photoemission process: Many-body effects
   - Matrix elements: unveiling the symmetries of the electronic state in the solid with polarized light.
   - Spectral function and self-energy: quantifying many-body interactions from ARPES
   - Experimental examples : Fermi liquid, electron-phonon interactions.

7) Experimental electronic structure of strongly correlated metals

   - Vanadates
   - High-Tc superconducting cuprates
   - 1D cuprates – spin/charge separation

8) Some systems of current interest and advanced ARPES-based techniques

   - 2D electron gases at the surface of transition-metal oxides
   - Spin-polarized states and topological materials
   - Hidden-order transition(s).
   - Spin-resolved ARPES, time-resolved ARPES, laser-ARPES

Recitations (TD):

9) *TD 1 – Mott transition via DMFT (dynamical mean field theory)*
10) *TD 2 – Rashba splitting at surfaces*

Evaluation: 1 oral exam (30 minutes) based on the reading of 2-3 papers provided two weeks before the exam.