Synchrotron Radiation and Ultrafast Laser Sources for the Study of Complex Materials

Marino Marsi

Laboratoire de Physique des Solides
CNRS UMR 8502 - Université Paris-Sud

marino.marsi@u-psud.fr

ICFP, October 10, 2012
• synchrotron radiation and fs lasers ↔ new materials

• Using light to understand underlying physics
• New materials created by ultrafast light pulses

• Correlated electrons, metal-insulator transitions
• FeAs superconductors: $\text{Ba(Fe}_{1-x}\text{Co}_x\text{)}_2\text{As}_2$
• Cuprate superconductors: $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$
• 3D Topological Insulators: $\text{Bi}_2\text{Te}_3$

• Unique opportunities on the Paris-Saclay campus
One of many synchrotron methods: ARPES

\[ E_L = h\nu - E_K - \Phi \]

Bands in k space: E vs k

Angle Resolved PhotoEmission Spectroscopy: a way of seeing electrons in reciprocal space

Contact: Amina Taleb (SOLEIL)
Strongly correlated materials

Correlation-induced metal to insulator transition (MIT) in strongly correlated materials:

\[ E^\uparrow \]

\[ E_F \]

\[
\begin{align*}
\text{d band} & \quad \rightarrow \quad \text{U} \\
\text{p band} & \quad \rightarrow \quad \text{charge gap}
\end{align*}
\]

Competition \[ \begin{cases} \text{Kinetic energy (t)} \\ \text{e--e interaction (U)} \end{cases} \]

Cr-doped V\(_2\)O\(_3\): textbook example of Mott-Hubbard transition
Metal-Insulator Transitions

Synchrotron Radiation for the study of strongly correlated materials:

⇒ Contact: Jean-Pascal Rueff (SOLEIL)

Lupi et al., Nature Communications. 1, 105 (2010)
100 years of superconductivity:

1911: Kamerlingh Onnes (Hg: Tc=4.2 K)
(1941: NbN Tc=16 K)

1957: BCS theory (phonon mediated SC)

1986: cuprates (CuO) Tc > 77 K

2008: pnictides (FeAs)

\[ \text{YBa}_2\text{Cu}_3\text{O}_{7-x} \]
High temperature superconductors

**Cuprates**
- Crystallographic structure: quasi-2D, Cu-O layers
- Example: Bi$_2$SrCaCuO

**Iron-pnictides**
- Crystallographic structure: less-2D than cuprates, Fe-As layers
- Example: BaFe$_2$As$_2$

**Electronic structure**
- Cuprates: single-band (Cu 3d$_{x^2}$)
- Iron-pnictides: multi-band (Fe 3d)

**Phase diagram**
- Cuprates: strongly-correlated, Mott insulator at low doping level
  - Ref: Damascelli et al., Rev. Mod. Phys. 75 (2003)
- Iron-pnictides: itinerant magnetism (SDW) at low doping level
  - Ref: Rullier-Albenque et al., PRL 103 (2009)

**Superconducting gap**
- Cuprates: d-wave symmetry
- Iron-pnictides: unknown (s+/−? Nodes or nodeless?)
FeAs superconductors: electronic structure

ARPES on Ba(Fe$_{1-x}$Co$_x$)$_2$As$_2$

Contact:
⇒ Véronique Brouet (LPS Orsay)

Brouet et al., PRB 80, 165115 (2009)
Ultrafast lasers ⇔ condensed matter

Femtosecond laser excitation

- e-e interaction: $T_e \gg T_{lattice}$
- e-phonon scattering: $T_e \downarrow T_{lattice} \uparrow$
- Thermalisation: $T_e \approx T_{lattice} \uparrow$
Ultrafast lasers ↔ condensed matter

Out of equilibrium condensed matter

- Excited electronic states
- Photoinduced phase transitions
- Coherent lattice oscillations
Ultrafast spectroscopy on Ba(Fe_{1-x}Co_x)_{2}As_2

Ultrafast reflectivity

Mansart et al., PRB 82, 024513 (2010)

Ultrafast reflectivity

x=0.08, T = 10 K, F=1.3 mJ/cm²

- e-phonon coupling: T_e ↓ T_{lattice} ↑
- electronic excitation: T_e >> T_{lattice}
- thermal relaxation: T_e ≈ T_{lattice}
coherent optical phonon in $\text{Ba(Fe}_{1-x}\text{Co}_x)\text{As}_2$

$A_{1g}$ mode: $f = 5.55$ THz

Laboratoire d’Optique Appliquée (ENSTA – X – CNRS)

Contact: Davide Boschetto (LOA)
fs laser + ARPES $\rightarrow$ FemtoARPES

Papalazarou et al., PRL 108, 256808 (2012)
femtoARPES on superconducting cuprates

Perfetti et al., PRL 99, 197001 (2007)

fs dynamics of SC gap:

→ Contact: Luca Perfetti (LSI-X)
Topological Insulators

Novel state of matter: insulating bulk conducting surface states

Dirac cone studied by ARPES
**Bi$_2$Te$_3$ topological insulator ⇔ femto ARPES**

n-type Bi$_2$Te$_3$

gap = 0.3 eV

probe: $h\nu = 6.28$ eV

pump: $h\nu = 1.5$ eV

Yazyev and al., PRL 105, 266806
Transient electronic structure
femtoARPES ↔ Topological Insulators

Ultrafast dynamics of Dirac fermions in topological insulators

Contact: Marino Marsi (LPS Orsay)

Hajlaoui et al., Nano Lett. 12, 3532 (2012)
The "Paris-Saclay" campus

Uniquely advantageous conditions for the study of materials with advanced synchrotron and laser based light sources