Non-linear optics with collective excitations and photoinduced superconductivity

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Outline

1. Motivation

2. Josephson Plasmons in YBCO

3. Phonon-plasmon interaction and parametric instability

4. Mechanism of previous signatures of photoinduced superconductivity:
   - Below Tc:
     Photoinduced reflection peak near lower plasmon edge and blue shift.
     Red shift of upper plasmon edge.
   - Above Tc: photoinduced blue shifted plasmon edge.
Experimental facts in pump and probe YBCO

1. Below Tc:
   - Higher energy peak appears near lower Josephson edge
   - Blue shift of the lower JP edge.
   - Red shift of the upper JP edge.

Experimental facts in pump and probe YBCO

2. Above \( T_c \):

- Photoinduced Josephson plasmon edge
- Renormalization of the plasmon frequency.

Mankowski et al., Structural Dynamics 4:044007 (2017)
3. Parametric generation of pair of Josephson plasmons:

A. Von Högen et al. forthcoming
Theory of Josephson plasmons

Superconducting bilayer

\[ \phi_1 \quad \rho_1 \quad \phi_2 \quad \rho_2 \]
\[ \phi = \phi_1 - \phi_2 \]
\[ \rho = \rho_1 - \rho_2 \]
\[ V = \mu_1 - \mu_2 \]

\[ \frac{\partial \phi}{\partial t} = V = \Gamma \rho \]
\[ \frac{\partial \rho}{\partial t} + J_\perp + \vec{\nabla}_\parallel \vec{j}_\parallel = 0 \]
\[ J_\perp = J_c \sin \phi \]
\[ \vec{j}_\parallel = \rho_s \vec{\nabla}_\parallel \phi \]

Neglecting in-plane variations

\[ \frac{d^2 \phi}{dt^2} = \Gamma \frac{d\rho}{dt} = -\Gamma J_\perp = -\Gamma J_c \sin \phi \]
\[ \omega_J^2 = \Gamma J_c \]

Josephson relation
Continuity equation
Interlayer Josephson current
In-plane superfluid current
Josephson plasmons in bilayer YBCO

Higher energy Josephson plasmon

14 THz

Lower energy Josephson plasmon

0.9 THz
Josephson plasmons in YBCO

First theoretical work on Josephson plasmons in YBCO: van der Marel, Tsvetkov, PRB (2001)

M. Michael et al.,

\[
\omega/\text{THz} = \epsilon_{\text{pl}} \left( \frac{q_x}{\text{THz} \times c^{-1}} \right)
\]
Apical oxygen phonon and Josephson plasmons in bilayer YBCO

Oxygen phonon

Higher energy Josephson plasmon

Lower energy Josephson plasmon

17 and 19.5 THz

14 THz

0.9 THz
Coupling between apical oxygen phonon and Josephson plasmons

Theory: M. Michael et al.

Phonon changes in-plane superfluid density

\[ \rho_{s,1} = \rho_{s,0} - Q(t) + \rho_1 \]

\[ \rho_{s,2} = \rho_{s,0} + Q(t) + \rho_2 \]

\[ \mathcal{H}_\parallel = \rho_{s1}(\nabla \phi_1)^2 + \rho_{s2}(\nabla \phi_2)^2 \]

Phonon plasmon interaction

\[ \mathcal{H}_\text{int} = Q((\nabla \phi_1)^2 - (\nabla \phi_2)^2) = Q(\nabla \phi_1 - \nabla \phi_2)(\nabla \phi_1 + \nabla \phi_2) \]

This argument correctly predicts frequencies of unstable modes: 14.5THz and 2.5THz

Coupling at finite \( Q_\parallel \)
Searching for most unstable modes

Instability Growth rate of Josephson plasmon pairs

Most unstable pair

Lower plasmon with $k_z = \frac{\pi}{D}$ at 2.5 THz

Upper plasmon with $k_z = \frac{\pi}{D}$ at 14.5 THz
Supercurrents break inversion – induce $X^{(2)}$

Oscillatory phonons and super currents induce voltage/currents

Use second harmonic generation to perform “instantaneous” measurement of inversion symmetry breaking
Experimental observation of three wave mixing process

Modes excited after the pump

- Coherent infrared mode spectrum

  - IR phonons
  - Josephson plasmon
  - Driven phonons

Scaling consistent with parametric resonance

- Dependence of driven phonon amplitude on $Q_{ir}$

  - Exponential fit
Josephson oscillations up to high temperatures

A. Von Högen et al.
Photoinduced superconductivity above Tc
Parametric driving making supercurrent fluctuations more coherent
Prediction of reflectivity spectra in pump and probe experiments in YBCO using this framework
Josephson plasmons and reflectivity of YBCO

Plasmon dispersion

Reflectivity

YBCO Josephson plasmon edge in equilibrium
Symmetries of collective modes and selection rules

<table>
<thead>
<tr>
<th>Mode</th>
<th>Reflection symmetry</th>
</tr>
</thead>
<tbody>
<tr>
<td>AO Phonon @ 17 THz</td>
<td>Odd</td>
</tr>
<tr>
<td>Neighboring phonon @ 19.5 THz</td>
<td>Odd</td>
</tr>
<tr>
<td>Lower plasmon, $k_z = \frac{\pi}{D}$</td>
<td>Odd</td>
</tr>
<tr>
<td>Upper plasmon, $k_z = \frac{\pi}{D}$</td>
<td>Even</td>
</tr>
<tr>
<td>Lower plasmon, $k_z = 0$</td>
<td>Odd</td>
</tr>
<tr>
<td>Upper plasmon, $k_z = 0$</td>
<td>Odd</td>
</tr>
</tbody>
</table>
Symmetries of collective modes and selection rules

Three wave processes:

Not Allowed

\[ \text{Phonon} \rightarrow \text{Lower plasmon, } k_z = 0 \rightarrow \text{Upper plasmon, } k_z = 0 \]

Allowed

\[ \text{Phonon} \rightarrow \text{Lower plasmon, } k_z = \frac{\pi}{D} \rightarrow \text{Upper plasmon, } k_z = \frac{\pi}{D} \]

Four wave processes:

Allowed

\[ \text{Phonon} \rightarrow \text{Lower plasmon, } k_z = 0 \]

\[ \text{Phonon} \rightarrow \text{Lower plasmon, } k_z = 0 \]

\[ \text{Phonon} \rightarrow \text{Lower plasmon, } k_z = 0 \]

\[ \text{Phonon} \rightarrow \text{Lower plasmon, } k_z = 0 \]

- Upper plasmon, \( \omega = \frac{\omega_0}{2} \)
- Lower plasmon, \( \omega = \frac{\omega_0}{2} \)

A. Von H"ogen et al. \( \text{forthcoming} \)

Driven phonons

\[ \omega/\text{THz} \]

\[ q_x/(\text{THz} \times c^{-1}) \]

Coherent infrared mode spectrum

\[ \text{Normalized FFT Amplitude} \]
Light reflection from Floquet medium and parametric amplification

- Oscillating currents and apical oxygens induce frequency mixing in the equations of motion.
- Incident beam couples to $k_z = 0$ Josephson plasmons. Find process that can couple to $k_z = 0$ and is closest to parametric resonance.
- Upon solving Fresnel-Floquet equations of motion, retain mixing only between $\omega_s$ and $\omega_{id}$. Use boundary conditions to find $k_s$ and $k_{id}$ for fixed $\omega_s$ and $\omega_{id}$.
- To determine orientation of $k_s$ and $k_{id}$ introduce infinitesimal damping and insist that the imaginary part is such that it decays away from the surface. Close to resonance the idler contribution propagates towards the surface corresponding to emission of energy from the oscillating material.
Example of Floquet modulation - Four wave mixing with two phonons

• Two neighboring phonons can act together as a single drive at their frequency difference.

• Assuming here that this frequency difference is 2.5 THz, this drive can parametrically drive a pair of lower Josephson plasmons at \( k_z = 0 \) relevant for reflectivity experiments.

• Effective Hamiltonian has the form:

\[
H = \sum_k \lambda_k <Q^2>(t) b_{1,k}b_{1,-k} + h.c.
\]
Parametrically amplified reflection on resonance

M. Michael et al.

Hu et al.,
Nature Materials
13:705 (2013)

See also N. L. Wang
Photoinduced plasmon edge above $T_c$

Air

YBCO

Incident

$\omega_s$

$\omega_{id}$

Reflected

$\omega_s$

$\omega_{id}$

Transmitted

$\omega_s$

$\omega_{id}$

$\kappa_s$

$\kappa_{id}$

M. Michael et al.

Hu et al.,
Nature Materials
13:705 (2013)
Renormalization of upper plasmon edge

Dominant driving mechanism

\[ \omega = 14.5 \text{ THz} \]

\[ Qz = 0 \]

\[ Qz = \pi/D \]

\[ \omega = 0 \text{ THz} \]

Floquet renormalization of upper plasmon edge

M. Michael et al.

Renormalization of upper plasmon edge

- **Level attraction:**
  In every parametric process where a drive with frequency, $\omega_d$, parametrically driving states at energies $\omega_1$ and $\omega_2$ then these states are:
  - **Blue shifted:** $\omega_1 + \omega_2 < \omega_d$
  - **Red shifted:** $\omega_1 + \omega_2 > \omega_d$
Summary – Effects of parametric resonance

- Floquet dressing of equilibrium modes.
- Parametric instability competes with dissipation and can make resonant modes more coherent.
- Parametric amplification in the reflectivity spectrum.
Summary

• Introduced a theory of JPs in YBCO coupled to phonons through superfluid renormalization.

• Can capture the phenomenology of various experiments both below and above Tc using a single framework.

• Highly suggestive of the pseudogap phase in YBCO.
Questions ?