ARPES: Uncovering the Superconducting Gap

Presentation for PHY601

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December 13$^{th}$, 2017
Outline

Introduction to ARPES

Seeing the superconducting gap

Conclusion
Photoelectric effect

Shining light on a metal expels photoelectrons;
Can measure their kinetic energy. **Does not depend on light intensity** \( I \)
Rather, depends on frequency \( \nu \)

\[
E_{\text{kin}} \propto \hbar \nu - \text{const}
\]
Einstein comes in: **quantization of light**
The constant is actually the work function $\phi$: **energy to delocalize electron from surface**.

$$E_{\text{kin}} = \hbar \nu - \phi$$
Angular Resolved Photo-Emission Spectroscopy

The gist of it:

Want to measure **energy of released electrons** $E_k$ and **their momentum** $k$

Use conservation laws and photoelectric effect to extract info

$$E_{kin} = \hbar \nu - \phi - |E_B|$$  \hspace{1cm} (1)
$$p_\parallel = \hbar k_\parallel = \sqrt{2mE_{kin}} \sin \theta$$  \hspace{1cm} (2)
\[ E_{\text{kin}} = \hbar \nu - \phi - |E_B| \]

\[ p_\parallel = \hbar k_\parallel = \sqrt{2mE_{\text{kin}}} \sin \theta \]

\( E_{\text{kin}} \) measured kinetic energy of outgoing electron

\( \theta \) measured is the angle of emission with the surface

\( \nu \) and \( \phi \) are known

\( E_B \) wanted binding energy of electron in metal

\( k_\parallel \) wanted crystal momentum

If one has that, we can construct the dispersion of the electrons \( E(k) \)!
Using ARPES, we measure the **actual** dispersion relation.

Interactions (e-e, e-ph, etc) change band dispersions and lifetimes (spread)

Measure the spectral intensity: \( I(k, \omega) \)

**Spectral intensity**

\[
I(k, \omega) \propto f(\omega) A(k, \omega)
\]

**1p spectral func.**

\[
A(k, \omega) = -\frac{1}{\pi} \frac{\Sigma''(k, \omega)}{[\omega - \epsilon_k - \Sigma'(k, \omega)]^2 + [\Sigma''(k, \omega)]^2}
\]

**Bare band**

\[
\epsilon_k
\]

**Self-energy**

\[
\Sigma(k, \omega) = \Sigma'(k, \omega) + i\Sigma''(k, \omega)
\]

= Band position + Linewidth/lifetime of QP
Free electron v.s. Fermi Liquid

ARPES can see difference between a non-interacting electron system and a Fermi Liquid system.

In NI $A(k,\omega) = \delta(\omega - \epsilon_k)$

Extremely sharp $\rightarrow$ Infinite lifetime of QP

In FL $A(k,\omega) = Z_k \frac{\Gamma_k/\pi}{(\omega - \epsilon_k)^2 + \Gamma_k^2} + A_{incoherent}$

QP peak has a width: finite lifetime $\tau_k = 1/\Gamma_k$
(Left) Theoretical band for Electron Phonon coupling, see the quasiparticle peak, which has a Lorentzian lifetime. (Right) Example of observed Arpes intensity for Bi2201
Experimental Considerations

Need a very clean surface (atomically flat). Hence **surface-sensitive probe**, not good on bulk! (probe $\sim 2 - 20\text{Å}$ in depth)

Need ultra-high vacuum (avoid surface deterioration)

Does not work under **pressure** or **magnetic field**.

**However**, very good at:

Comparison to theory

High resolution in energy AND momentum
Bad surface

**Figure:** Experiments on optimally doped Bi2212 (a) Dispersion right after cleaving. (b) After 1h in pure nitrogen. (c) After 1h in air.
We see the $\epsilon_k = \frac{k^2}{2m^*}$ the free dispersion of Copper. The splitting of the bands can even be observed, due to Rashba coupling (spin-momentum locking, small but non-zero in Cu[111]).
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Superconductivity Essentials

- Cooper instability: small attractive interaction binds electrons together \( |k \uparrow, -k \downarrow \rangle \)
- In BCS theory, superconductivity is result of condensation of the Cooper pairs.
- Conventional SC: attraction is due to retarded electron-phonon interaction. Isotropic interaction.

\[
H = \sum_k \xi_k c_k^\dagger c_k + \xi_k c_{-k}^\dagger c_{-k} + \Delta c_{-k}^\dagger c_{k} + \Delta c_{-k} c_k
\]  
(3)

\[
\xi_k = \frac{\hbar^2 k^2}{2m} - \mu
\]  
(4)
What is the gap

- Because of the pairing state, there is an energy gap for single particle excitation.
- In a superconductor, there is a one-particle gap but no two-particle gap.
- The two-particle excitations (Cooper pairs) are coherent and transport current without resistance.
Example: Niobium

We can probe the DOS close to the Fermi Surface for Niobium ($T_c = 9.26\,K$)

For $T > T_c$, no peak below $E_F$, normal Fermi distribution.

For $T < T_c$, gap opens, superconductivity sets in.
S-Wave vs D-Wave

○ In conventional SC, attractive interaction due to e-ph coupling: isotropic. Leads to **s-wave** pairing (gap positive all around FS).

○ In Cuprates, a **d-wave** pairing was advanced to explain how they could have SC behavior.

○ D-wave → has nodes where \( \Delta(\mathbf{k}) = 0 \) on the Fermi Surface
Bi-2212: Fermi Surface

- Bi2212: $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$, $T_c^{\text{max}} = 96K$.
- Planes of CuO with “stuff” in between. Fermi surface is similar to YBCO (as in homework)
Bi-2212: Gap across FS

- Using ARPES, the excitations near the Fermi-Surface can be probed very accurately.
- Doing different cuts in $k$-space, we can probe different parts of the Fermi-Surface.
A clear node

$E_F$ from polycrystalline metal. Gap is hard to read, but is there!
Exceptional resolution of the electronic structure (Bands & Fermi Surface);
Can explicitly probe the gap;
Answered many questions about the nature of the electronic excitations in Cuprates (ex: gap symmetry + deviations);
In Cuprates, has been very important to ascertain the presence of the pseudogap phase (gap but no SC);
To be used even more: Need materials with better surface cleaving (currently being applied to pnictides Fe-based SC)
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References

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I. M. Vishik et al. PNAS 109 (45) 18332–18337 (2012)
Thanks for listening!

Questions?