ARPES: Uncovering the Superconducting Gap

Presentation for PHY601

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Outline

Introduction to ARPES

Seeing the superconducting gap

Conclusion

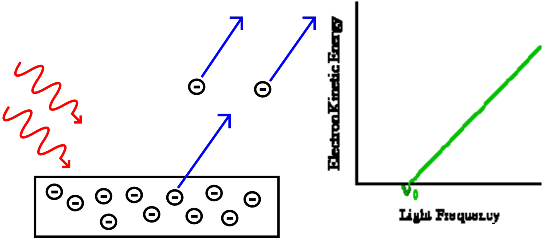
Photoelectric effect

Shining light on a metal expulses *photoelectrons*;

Can measure their kinetic energy. **Does not depend on light intensity I**

Rather, depends on frequency ν

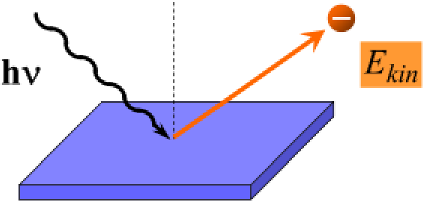
$$E_{kin} \propto \hbar\nu - const$$

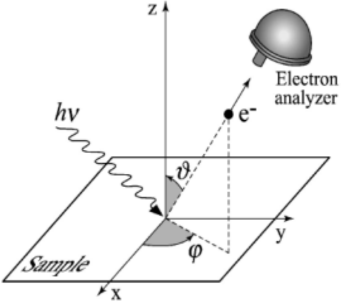


Einstein comes in: **quantization of light**

The constant is actually the work function ϕ: **energy to delocalize electron from surface**.

$$E_{kin} = \hbar\nu - \phi$$





ARPES: theory

Angular Resolved Photo-Emission Spectroscopy

The gist of it:

Want to measure **energy of released electrons** E_k and **their momentum** $\boldsymbol{k}$

Use conservation laws and photoelectric effect to extract info

$$E_{kin} = \hbar\nu - \phi - |E_B| \tag{1}$$

$$\boldsymbol{p}_{\parallel} = \hbar\boldsymbol{k}_{\parallel} = \sqrt{2mE_{kin}}\sin\theta \tag{2}$$

$$E_{kin} = \hbar\nu - \phi - |E_B|$$
$$\boldsymbol{p}_{\|} = \hbar\boldsymbol{k}_{\|} = \sqrt{2mE_{kin}}\sin\theta$$

E_{kin} measured kinetic energy of outgoing electron

θ measured is the angle of emission with the surface

ν and ϕ are known

E_B wanted binding energy of electron in metal

$\boldsymbol{k}_{\|}$ wanted crystal momentum

If one has that, we can construct the dispersion of the electrons $E(k)$!

From Many-Body interpretation

Using ARPES, we measure the **actual** dispersion relation.

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

Measure the spectral intensity: $I(\boldsymbol{k},\omega)$

Spectral intensity $$I(\boldsymbol{k},\omega) \propto f(\omega)A(\boldsymbol{k},\omega)$$

1p spectral func. $$A(\boldsymbol{k},\omega) = -\frac{1}{\pi}\frac{\Sigma''(\boldsymbol{k},\omega)}{[\omega-\epsilon_k-\Sigma'(\boldsymbol{k},\omega)]^2+[\Sigma''(\boldsymbol{k},\omega)]^2}$$

bare band $$\epsilon_k$$

Self-energy $$\Sigma(\boldsymbol{k},\omega) = \Sigma'(\boldsymbol{k},\omega) + i\Sigma''(\boldsymbol{k},\omega)$$

$=$ Band position $+$ Linewidth/lifetime of QP

Free electron v.s. Fermi Liquid

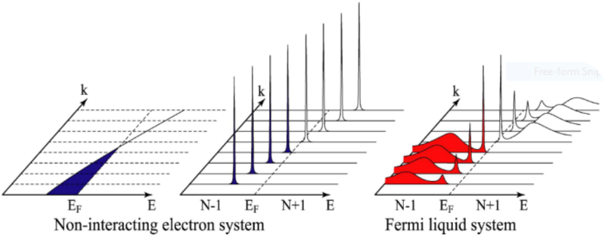
ARPES can see difference between a **non-interacting** electron system and a **Fermi Liquid** system.

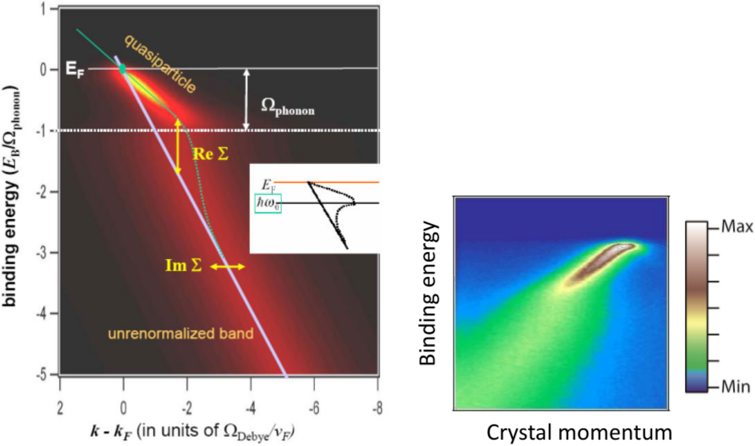
In NI $A(\boldsymbol{k},\omega) = \delta(\omega - \epsilon_k)$

Extremely sharp → Infinite lifetime of QP

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

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 $\sim 2 - 20$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

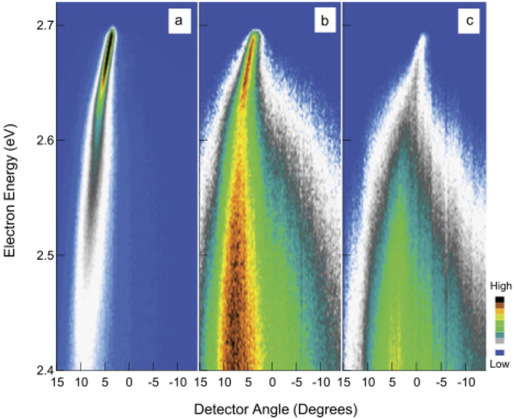
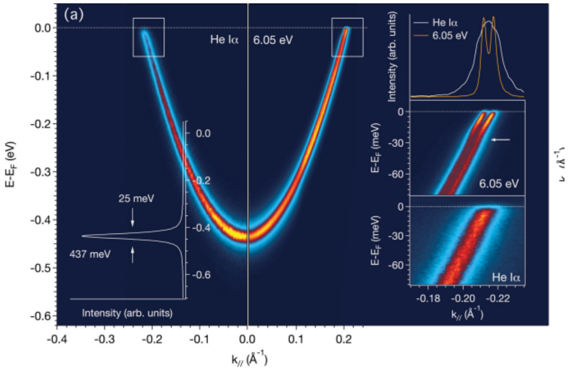


Figure: Experiments on optimally doped Bi2212 (a) Dispersion right after cleaving. (b) After 1h in pure nitrogen. (c) After 1h in air.

A clean example: Cu



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

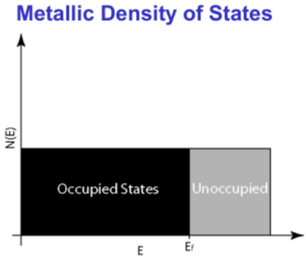
- Cooper instability: small attractive interaction binds electrons together $|\boldsymbol{k}\uparrow, -\boldsymbol{k}\downarrow>$
- In BCS theory, superconductivity is result of condensation of the Cooper pairs.
- Conventional SC: attraction is due to retarded electron-phonon interaction. Isotropic interaction.

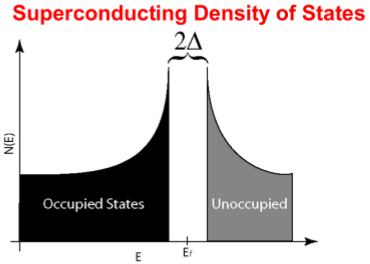
$$H = \sum_{\boldsymbol{k}} \xi_k c^\dagger_{\boldsymbol{k}\uparrow} c_{\boldsymbol{k}\uparrow} + \xi_k c^\dagger_{\boldsymbol{k}\downarrow} c_{\boldsymbol{k}\downarrow} + \Delta c^\dagger_{\boldsymbol{k}\uparrow} c^\dagger_{-\boldsymbol{k}\downarrow} + \Delta c_{-\boldsymbol{k}\downarrow} c_{\boldsymbol{k}\uparrow} \tag{3}$$

$$\xi_k = \frac{\hbar^2 \boldsymbol{k}^2}{2m} - \mu \tag{4}$$

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.


Metallic Density of States

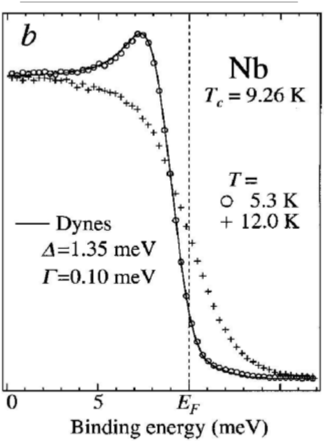

Superconducting Density of States

Example: Niobium

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

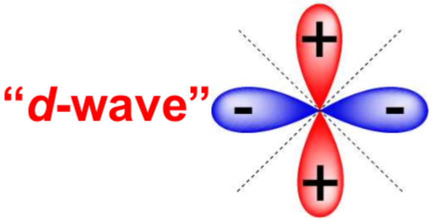
For $T > T_c$, no peak below E_F, normal Fermi distribution.

For $T < T_c$, gap opens, superconductivity sets in.



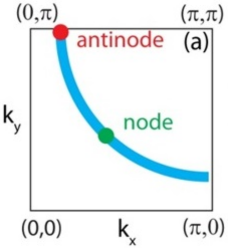
S-Wave vs D-Wave

- 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 $\Delta(\boldsymbol{k}) = 0$ on the Fermi Surface



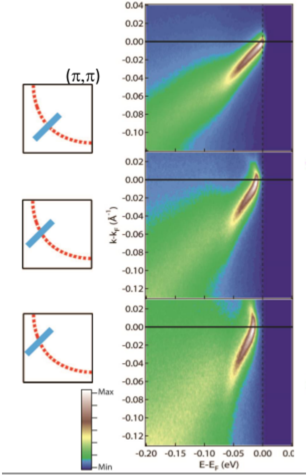
Bi-2212: Fermi Surface

- Bi2212: $Bi_2SR_2CaCu_2O_{8+\delta}$, $T_c^{max} = 96K$.
- Planes of CuO with “stuff” in between. Fermi surface is similar to YBCO (as in homework)

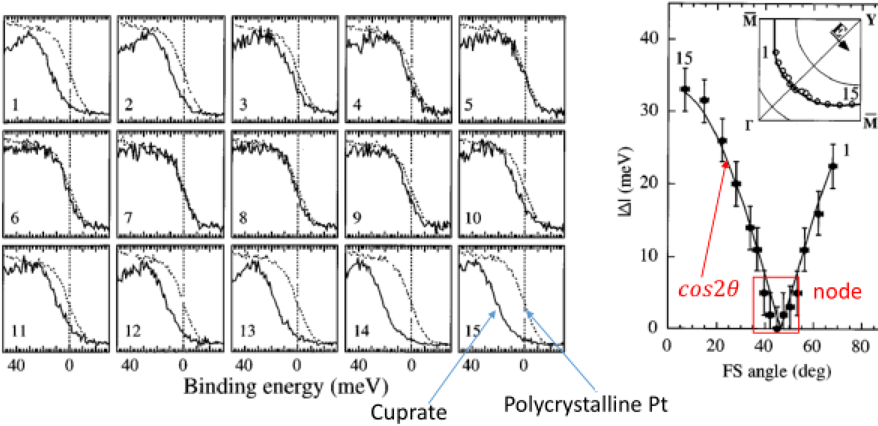


Bi-2212: Gap across FS

- ○ 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



Cuprate

Polycrystalline Pt

$cos2\theta$

node

E_F from polycrystalline metal. Gap is hard to read, but is there!

What to take from this

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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Thanks for listening!

Questions?