Measuring Fermi Surfaces in Extreme Magnetic Fields

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Starting point: carriers in a periodic potential

\[ E(k, q) = \frac{\hbar^2 k^2}{2m} \]

Kinetic Energy

\[ E(k, q) = \frac{\hbar^2 k^2}{2m} + V(q) \]

Kinetic + Periodic/ionic potential

\[ E_F \]

(or Fermi level)
What is a Fermi surface?

The location in reciprocal space of long-lived electronic excitations that govern the electronic properties of metals at low temperatures.

“The” fundamental property of the metallic state.

“The pathways for carriers through a metal”
Geometry of the FS: determined by crystal structure and position of the Fermi level

\[ \text{Nb}_2\text{Pd}_{0.81}\text{S}_5 \]


Wien2K
Electronic anisotropy and geometry of the Fermi surface

Na, bcc

Co, hcp

3-D


http://www.phys.ufl.edu/fermisurface/
Two-dimensional Fermi surfaces

$YBa_2Cu_3O_{7-\delta}$

$E(k)$

SrFe$_2$P$_2$

1) 

2) 

3) 

4) 

Quasi-one-dimensional Fermi surfaces

$$(\text{TMTSF})_{2}\text{PF}_6$$

$$\hbar \vec{v} = \vec{\nabla}_k E(k)$$
Lindhard Function and Peierls Instability

Response function of the \( \bar{\epsilon} \) gas:

\[
\rho^{\text{ind}}(\bar{q}) = \chi(\bar{q})\phi(\bar{q})
\]

\[
\chi(\bar{q}) \sim \frac{e^2}{\pi \hbar v_F} \ln \left| \frac{1 + q / 2k_F}{1 - q / 2k_F} \right|
\]


 Courtesy: L. Alcacer
(Per)$_2$Au(mnt)$_2$

Resistance (Ohms) vs Temperature (K)

Metal
CDW

$T_{CDW}$

Magnetic Field (T)

$T_{CDW}(B=0)$
$T_{CDW}(B∥b-axis)$
$T_{CDW}(B⊥b-axis)$
Landau Quantization in a magnetic field

\[ \mathbf{B} = \nabla \times \mathbf{A}; \text{where } \hat{\mathbf{A}} = \begin{pmatrix} 0 \\ B_x \\ 0 \end{pmatrix} \text{ if } B = B_0 \hat{z} \]

\[ \hat{H} = \frac{1}{2m} \left( \hat{\mathbf{p}} - e\hat{\mathbf{A}} \right)^2 = \frac{\hbar^2 k_x^2}{2m} + \frac{(\hbar k_y + eBx)^2}{2m} + \frac{\hbar^2 k_z^2}{2m} \]

\[ \hat{H} = \frac{1}{2m} \left[ \hbar^2 k_x^2 + m^2 \omega_c^2 (x - x_0)^2 \right] + \frac{\hbar^2 k_z^2}{2m} \]

where \( \omega_c = \frac{eB}{mc} \) and \( x_0 = \frac{\hbar k_y}{m\omega_c} \);

\[ E_{n,k_z} = \hbar \omega_c \left( n + \frac{1}{2} \right) + \frac{\hbar^2 k_z^2}{2m} \]

Introduction to Q.M. by Griffiths

Clean samples and low temperatures!
Electronic orbits in a magnetic field: the Onsager relation

Bohr – Sommerfeld quantization rule:

\[ \oint \vec{p} \cdot d\vec{r} = \left( n + \frac{1}{2} \right) \hbar \]

where \( \vec{p} = \hbar \vec{k} - \frac{e}{c} \vec{A} \) and \( \hbar \vec{k} = \frac{e}{c} \vec{r} \times \vec{B} \);

\[ \Rightarrow \frac{e}{c} \left( \oint (\vec{r} \times \vec{B}) \cdot d\vec{r} + \oint \vec{A} \cdot d\vec{r} \right) = \left( n + \frac{1}{2} \right) \hbar \]

\[ \Rightarrow \frac{e}{c} \left( -B \oint \vec{r} \times d\vec{r} + \int \nabla \times \vec{A} \cdot ds \right) = \left( n + \frac{1}{2} \right) \hbar \]

\[ \Rightarrow \Phi_n = B.S_r = \left( n + \frac{1}{2} \right) \phi_0 \]

where \( \phi_0 = \frac{\hbar c}{2e} \) is the quantum of flux (CGS units)

**Introduction to Solid State Physics** by Charles Kittel
Typical organic conductor: \((\text{Donor})_2\text{Anion}\)

\[
\tau-(P-(S,S)-\text{DMEDT-TTF})_2(AuBr_2)_{1+y}
\]

Increase the magnetic field and the Landau levels (red) begin to shift past the Fermi surface (blue).

![Normalized resistance](image1)

![FFT](image2)

FFT
Frequency $\sim 494$ T
What if you rotate the sample?

$$S_0 \propto \frac{1}{\cos(\theta)}$$

where \(\theta\) is the angle between the field and sample axis.

$$\text{BaFe}_2\text{As}_2$$

Issues with the (fast) Fourier transform...

\[ R (\text{m}\Omega) \]

\[ H (\text{T}) \]

\( T = 0.6 \text{ K} \)

\( \text{Na}_{0.84}\text{CoO}_2 \)

\[ (1/\rho - 1/\rho_b)\rho_b \]

\[ H^{-1}(\text{T}^{-1}) \]

\[ T = 0.6 \text{ K} \]
\[ 1.5 \text{ K} \]
\[ 2.5 \text{ K} \]
\[ 3.1 \text{ K} \]
\[ 4.2 \text{ K} \]

\[ F_1 = 125 \text{ T} \]
\[ F_2 = 190 \text{ T} \]
\[ 2 \times F_1 \]

\[ \text{FFT amp } T^{-1} \text{ (Arb. Units)} \]

\[ F (\text{T}) \]

\[ T = 0.6 \text{ K} \]
\[ T = 1.5 \text{ K} \]
\[ T = 2.5 \text{ K} \]
\[ T = 3.1 \text{ K} \]
\[ T = 4.2 \text{ K} \]

\[ \text{Suchitra E. Sebastian et al., Nature 454, 200 (2008)} \]

\[ \text{Better S/N ratio and enough wiggles (quantum oscillations)} \]

\[ \text{Luis Balicas et al., PRL 100, 126405 (2008)} \]
When one gets more wiggles…


\[
F = F_0 + \Delta F
\]

where \( F_0 = 530 \, \text{T} \)

and \( \Delta F = 90 \, \text{T} \)
Techniques

AC-susceptibility: \( M_{AC} = \frac{dM}{dH} H_{AC} \sin \omega t \)

Detection circuit

Detection coil (superconducting)

Excitation coil

Good (even) for nearly isotropic Fermi surfaces

Magnetostriction: \( \frac{\Delta L}{L} (H) \)

G. M. Schmiedeshoff et al., RSI 77, 123907 (2006).

\[ \tau \propto \frac{1}{F} \frac{dF}{d\theta} MB \]

torque-magnetometry, capacitive

torque-magnetometry, piezo resistive

Good for anisotropic (Q2D) Fermi surfaces
Techniques – an example and practical considerations

AC-susceptibility: \[ M_{AC} = \frac{dM}{dH} H_{AC} \sin \omega t \]

Detection coils (blue):
- 1000s of turns using 12 – 50 µm wire
- “wet” wound using epoxy to fill any space
- Balanced within ~ 1 turn
- Use a well machined former in a coil winder

Freq = 777 Hz
Drive current = 5 mA
Techniques….(cont.)

- Clean single crystals with good RRR
- 4 contacts (at least) to avoid wire resistance as part of the measurement.
- Reasonable currents for good S/N ratio but to avoid self-heating….this also means low resistance contacts.


$V = IR$

$P = I^2 R$
• **TDO – tunnel diode oscillator**
  • Resonant circuit with frequencies ~ 20 – 500 MHz
  • Changes in the sample conductivity are observed by changing the coil inductance and the frequency at the ppm level.

$$f_0 = \frac{1}{2\pi\sqrt{LC}}$$

The Lifshitz-Kosevich formalism

For a given oscillatory component:

\[
\left( \frac{\vec{M}, \vec{\sigma}}{\sigma_b} \right) \propto \sum_{p=1}^{\infty} \left( \frac{-1}{p^{3/2}} \right) R_{T,p} R_{D,p} R_{s,p} \cos \left[ 2\pi p \left( \frac{F}{B} - \gamma \right) \pm \frac{\pi}{4} \right];
\]

\[
R_{T,p} = \left( \alpha \mu T / B \right) / \sinh(\alpha \mu T / B);
\]

\[
R_{D,p} = \exp(-\alpha \mu T_D / B);
\]

\[
R_{s,p} = \cos \left( \frac{\pi}{2} p g \mu / m_e \right)
\]

$\mu$ is the quasiparticle effective mass

$\alpha = 2\pi^2 k_B m_e / e\hbar = 14.7$ T/K;

$T_D = \hbar / 2\pi k_B \tau$ (the Dingle temperature)

$m_e$ (is the bare electron mass)

Spin-zero angles: spin-up and spin-down Fermi surfaces interfere destructively.

Useful for, for ex., evaluating $g$

Using our Fermi surface data

CeRhIn$_5$

- Transport, heat capacity and dHvA via pulsed fields and capacitance cantilever in dc fields.
- Each technique helps tell part of the story of the evolution of the Fermi surface
Yamaji oscillations

$\beta$-(BDA-TTP)$_2$SbF$_6$


$\tan \theta = \frac{\pi}{ck_F} (n - 1/4)$

Application to cuprates

YBa$_2$Cu$_3$O$_{6+x}$  \( x = 0.56 \)

S. Sebastian, et al., PRB 81, 214524 (2010)
**Instrumentation – Two-axis rotation**

- Use an Attocube rotation system to add a $\phi$ component to rotation.
- Labview software has been used to make a user interface for aligning samples and automating measurements (work in progress).

![Graph showing resistance vs. angle](image_url)
Magnetic Breakdown and Quantum Interference

Stark quantum interference

\[ B_{MB} = \frac{m^* E_g^2}{\hbar e E_F} \]


Magnetic breakdown


Q1D closely spaced Fermi surfaces

\((\text{Per})_2\text{Au(mnt)}_2\)

\((\kappa-(ET))_2\text{Cu(NCS)}_2\)
A new approach: Sweeping the Fermi level


Summary

- Fermi surfaces (FS) can be calculated from known RT lattice but cannot be trusted….measurements are needed.
- We have a large variety of experimental techniques to determine the temperature and angular dependence of the FS.
- From our data we can get the effective mass, scattering rates map out the shapes of the orbit(s) and learn something about the interactions that are important in a material.
- AMRO is powerful way to extract the cross-section of two-dimensional Fermi surfaces.
- Conventional techniques used for Fermi surface studies (transport, AC susceptibility, torque magnetometry…) are always being improved and modified,
  - New methods are being used with thin, carefully engineered devices (gate sweeping).
- If you think of a great idea for a Fermi surface measurement, please talk to a NHMFL user support scientist and let’s try it.

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References & Resources

Fermiology
• *Band Theory and the Electronic Properties of Solids* by John Singleton
• *Magnetic Oscillations in Metals* by David Shoenberg
• *Solid State Physics* by Neil Ashcroft and David Mermin
• *Introduction to Solid State Physics* by Charles Kittel

High Pressure
• *High Pressure Experimental Methods* by M. Eremets

“Hands-on” Knowledge
• *Experimental Techniques and Low Temperature Measurements* by Jack Ekin

THANKS!