Electronic Origin of High-Temperature Superconductivity in Single-Layer FeSe Superconductor*

Team #1 - Jyoti Aneja, Brian Busemeyer, Mindy Cartolano, David Casavant

Physics 596 Journal Club Presentation
November 22, 2013

Outline

● Background
  ○ Fermi surfaces
  ○ Superconductivity
● Article summary
  ○ Methods
  ○ Results
● Critique of Paper
● Conclusions
● Citation Analysis
Fermi Surfaces Depict Conduction States in k-space

Along one dimension...

Kittel, 2005, John Whiley & Sons, 8e, 181
Fermi Surfaces Depict Conduction States in k-space

Along one dimension...

...in two dimensions...

Kittel, 2005, John Whiley & Sons, 8e, 181

PRL 106, 187001 (2011)
Fermi Surfaces Depict Conduction States in k-space

Along one dimension...

...in two dimensions...

...intersecting with Fermi energy.

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Another Kind of Fermi Surface:

Have “two band” Fermi surface...

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...see extra circle in center.
Brief review: Connecting Iron-based Superconductivity and Magnetism

Table 1 | Properties of different classes of superconductor

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Conventional superconductors: Electron-phonon interactions lead to Cooper pairing

Unconventional superconductors: Antiferromagnetism suggests magnetic interactions are involved.

“Nesting picture” : magnetic interactions require a k-vector connecting parts of Fermi surface with opposite sign in order parameter.
Aforementioned Symmetries of the Fermi Surface and Order Parameter:

s-wave (conventional superconductivity)
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- **2-band s(+/−) -wave**
Of All the High-$T_c$ Fe-based Superconductors, Why Study Monolayer FeSe?

- Simple crystal structure: a single FeSe layer
- 2D electronic structure
  - Entire 3D momentum space doesn’t need to be probed
- Superconducting phase is pure, as opposed to $A_xFe_{2-y}Se_2$ superconductors which contain many coexisting phases.
- FeSe is a building block for Fe-based superconductors
Sample Preparation: Molecular Beam Epitaxy

- The single-layer FeSe is grown on a STO substrate*
- Se molecular beam etching to produce an atomically smooth STO surface

High-resolution Angle-Resolved Photoemission (ARPES) Measurements

Goal: measure energy and momentum of outgoing electron

\[ E = \hbar \omega - E_{k_f} - \phi. \]

\[ \hbar k_{i||} = \hbar k_{f||} = \sqrt{2mE_f \sin \theta} \]

Image courtesy of Wikipedia
Distinguishing Features of Electronic Structure

- Electron-like Fermi surface sheet around M
- Lacks a hole-like Fermi-surface around the gamma point
- Rules out 2-band s-wave order parameter symmetry: requires scattering between hole-like bands near gamma and electron-like bands near M

Fermi Surface Mappings

Gamma Point
$T_c$ Inferred From Measurement of the Superconducting Gap

- The superconducting gap is inferred from photoemission spectra along a cut at the M3 point.

Symmetrized photoemission spectra
\( T_c \) Inferred From Measurement of the Superconducting Gap

- The superconducting gap is inferred from photoemission spectra along a cut at the M3 point.
- The gap size is measured to be \( \approx 15 \) meV at 20K.
- Vanishing gap at high temperatures indicates \( T_c = 55 \pm 5 \) K.
Evidence for a Nodeless Superconducting Gap

- Photoemission spectra are obtained for different momenta
  - Done independently for two samples
- The gap is nearly isotropic, indicating that there is no node
- Rules out d-wave order parameter symmetry
Critique 1: $T_c$ Cannot be Measured Directly
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- Comparison calculation:
  \[(T_c)_{\text{FeSe}} = (\text{Gap Size})_{\text{FeSe}} \times \left( \frac{T_c}{\text{Gap size}} \right)_{(\text{Tl,Rb})_{x} \text{Fe}_{2-y} \text{Se}_2} \]
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$$ = (15 \text{ meV}) \left( \frac{32 \text{ K}}{9.7 \text{ meV}} \right) \approx 50 \text{ K} $$
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(13 ± 2 meV vs. 15 ± 2 meV)
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- Different post-annealing conditions could change the superconducting phase
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(13 ± 2 meV vs. 15 ± 2 meV)

- Different post-annealing conditions could change the superconducting phase

- Both samples show no gap at Fermi surface (no effect on nodeless superconducting gap conclusion)
Critique 3:
Lack of a Two-Gap Structure Disagrees with Previous Tunneling Measurements*

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- Could the interface between FeSe and STO substrate superconduct with different gap sizes?
  - Band-structure calculations
  - No signature of a 2D electron gas in the interface

Critique 3: Lack of a Two-Gap Structure Disagrees with Previous Tunneling Measurements*

- Could the interface between FeSe and STO substrate superconduct with different gap sizes?
  - Band-structure calculations
  - No signature of a 2D electron gas in the interface

- How does annealing to substrate change FeSe structure?
  - Lattice mismatch may cause strain which increases superconductivity

Critique 4: Style of the Paper

- The authors do address potential points of controversy well
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● Grammar
  ○ “They will shed lights on understanding the superconductivity mechanism and exploring new superconductors with higher $T_c$ in the Fe-based superconductors.” (DOI: 10.1038/ncomms1946)
Paper Conclusions

- Single-layer FeSe has a much simpler structure, but is likely to have one of highest $T_c$'s of the Fe-based superconductors.

- Measurements show lack of a hole-like Fermi surface at gamma point and a nodeless, isotropic superconducting gap.

- Current theories for the superconducting mechanism need to be modified to describe all the results presented in this paper.
Citation Analysis

- Since publication in July 2012, the paper has been cited
  - 17 times (Google Scholar)
  - 16 times (Scopus)

- Because FeSe has the simplest crystal structure of the Fe-based superconductors discovered so far, it is considered to be the essential building block for superconductivity in the Fe-based compounds. As such, the paper has been applied and cited by both theoretical and experimental groups.
Theory

“$S_4$ Symmetric Microscopic Model for Iron-Based Superconductors”, “Mechanism for Odd Parity Superconductivity in Iron-Based Superconductors” : Jiangping Hu, Ningning Hao et al.

The more recent paper in Nature “Superconductivity: Fewer atoms, more information” : Sergey Borisenko, talks about how monolayer FeSe might be an ideal model system for testing theoretical ideas.

Experiment

“Superconductivity and magnetism in 11-structure iron chalcogenides in relation to the iron pnictides” : David Joseph Singh

“Single crystal growth and characterization of tetragonal FeSe$_{1-x}$ superconductors” : Dmitriy Chareev et al.
Acknowledgements: We would like to thank Prof. Lance Cooper for his guidance and feedback during the preparation of this talk.

Thank you for listening!