Superconductivity in $\text{Cu}_x\text{Bi}_2\text{Se}_3$ and its Implications for Pairing in the Undoped Topological Insulator


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Outline of Talk

• Background and motivation
• Structure and synthesis of $\text{Cu}_x\text{Bi}_2\text{Se}_3$
• Measurement and characterization of superconductivity in $\text{Cu}_x\text{Bi}_2\text{Se}_3$
• Critiques and impact of paper
Topological Insulators

• Recently discovered state of matter that behaves like an insulator in its bulk (interior) and a conductor on its surface

• Surface states are “spin currents” -- spin-up and spin-down electrons propagating in opposite directions

Surface States and Superconductivity

• It has been theorized that exotic quasiparticles could be generated and manipulated by depositing a superconductor on the surface of a topological insulator

• An experimental realization of these quasiparticles would be an important proof of concept for particle physicists, and could significantly advance experimental quantum computation
Research Motivation

• Hor et al. demonstrate that superconductivity can be induced in the topological insulator Bi$_2$Se$_3$ through intercalation of copper atoms.
• Bi$_2$Se$_3$ is made from double layers of BiSe$_6$ octahedra

• Cu may either intercalate between the Se layers, Cu$_x$Bi$_2$Se$_3$
  or substitute for Bi, Bi$_{2x}$Cu$_x$Se$_3$

• They have substantial differences in the electrical properties
Crystal growth

• Melt stoichiometric mixtures of Bi (99.999%), Cu (99.99%), and Se (99.999%) at 850°C

• Slow cooling from 850 to 620 °C

• Quenching in cold water

http://www.sttic.com.ru/lpcbc/DANDP/Bi-Ch.html
Structural analysis

X-ray diffraction scan

Electron diffraction pattern

High resolution electron microscope image
Structure Analysis Results 1

• Single crystal is chemically single phase
• Excellent crystalline quality on the long range
• Good crystal quality on the nanoscale
• However, no long or short range ordering of the Cu in the interstitial sites
Structure Analysis Results 2

(001) surface of a cleaved \( \text{Cu}_{0.15}\text{Bi}_2\text{Se}_3 \) single crystal using an STM at 4.2 K.

- type 1: located on the cleaved surface and are clusters of intercalated Cu atoms
- type 2: intercalated Cu in Van der Waals layers beneath the surface
- type 3: requires further study
Structure Analysis Results 2

(001) surface of a cleaved Cu$_{0.15}$Bi$_2$Se$_3$ single crystal using an STM at bias voltages of

(a) -1.0 V
(b) -0.5 V
(c) +0.5 V
(d) +1.0V.
Zero-field- and field-cooled magnetization of Cu$_x$Bi$_2$Se$_3$

- Cu$_{0.12}$Bi$_2$Se$_3$: $T_c = 3.8$ K
- 20% of expected magnetization
Zero-field- and field-cooled magnetization of Cu$_x$Bi$_2$Se$_3$

- Cu$_{0.12}$Bi$_2$Se$_3$: $T_c = 3.8$ K
- 20% of expected magnetization

- Cu$_x$Bi$_2$Se$_3$ superconducts for $0.1 \leq x \leq 0.3$
- Other samples do not superconduct
Temperature dependent resistivity of $\text{Cu}_x\text{Bi}_2\text{Se}_3$

- Carrier density $\approx 2 \times 10^{20} \text{ cm}^{-3}$
- $T_c = 3.8 \text{ K}$
- Non-vanishing resistivity

Blow up of figure on the left
Temperature dependent resistivity of Cu$_x$Bi$_2$Se$_3$

Magnetoresistance at 1.8 K for H $\parallel$ c

![Magnetoresistance graph](image1.png)

Critical field as a function of temperature along basal plane and c axis

![Critical field graph](image2.png)

Temperature-dependent critical field at 0.3K:
- $H \parallel c$: $H_{c2} = 1.7$ T
- $H \parallel ab$: $H_{c2} = 4.6$ T
Conclusion

- **Cu** intercalation in Van der Waals gaps between **Bi$_2$Se$_3$**
- Superconductivity of **Cu$_x$Bi$_2$Se$_3$$** at 3.8K with $x$ (0.12$\sim$0.15)
Critique

• **Credibility** The model is reasonable and the experimental process is standard, the data is credible

• **Innovation** The first time that Cooper pairing is reported in topological insulator, may have impact on future work
Unsolved Problems & Future Work

- $\text{Bi}_2\text{Se}_3 \rightarrow \text{Bi}_2\text{Te}_3$ ?
- The specific heat of $\text{Cu}_x\text{Bi}_2\text{Se}_3$. (Has been done by Group 5’s paper)
- Specific layer? Or The material itself?
- Replace Cu with other element and show similar result?
The Importance of Our Paper

• Our paper is an original work, it’s the first experimental reporting of superconductivity in a topological insulator

• Important for future quantum computation. (Majorana fermion)
Citing Information

- Very hot, 43 times/ past 1 year
- Still in basic researching stage

Journals (43 Total)
- Physical Review B (17)
- Physical Review Letters (7)
- JETP Letters (2)
- Journal of Applied Physics (2)
- Nature Physics (2)
- Reviews of Modern Physics (2)

Annual Review of Condensed
- Matter Physics (1)
- MRS Proceedings (1)
- Review of Scientific
- Instruments(1)
- Physica E: Low-dimensional
- Systems and Nanostructures (1)
Thanks!