Topological superconductivity in Pb/Co/Si(111)

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Outline

• I-Magnetic bound states in superconductors
  Dimensionality effect
  2H-NbSe2
  Pb/Si(111)

• II-Topological superconductivity in ferromagnet-superconductor hybrid systems
  1D vs 2D case
  Majorana dispersion at the edge of a 2D system
  Majorana bound states in vortex cores
Classical magnetic impurities in a superconductor

Classical impurity approximation: the impurity behaves as a local magnetic field

\[ \hat{H}_{imp} = J \sum_{k} \hat{\vec{s}}_{I} \cdot \hat{\vec{s}}_{k} \]

\[ \hat{\vec{s}}_{I} \cdot \hat{\vec{s}}_{k} > 0 \]

\[ \hat{\vec{s}}_{I} \cdot \hat{\vec{s}}_{k} < 0 \]
Magnetic impurities: Interaction mechanism

Appearance of in-gap Yu-Shiba-Rusinov bound states localized around the magnetic impurity

\[ \hat{H}_{\text{imp}} = J \sum_{k} \hat{S}_l \cdot \hat{S}_k \]

\[ \psi_{\pm}(r) = \frac{1}{\sqrt{N}} \frac{\sin (k_F r + \delta^\pm)}{k_F r} e^{-\Delta \sin(\delta^+ - \delta^-)r/\hbar v_F} \]

\[ E = \Delta \cos(\delta^+ - \delta^-) \]

\[ \tan \delta^\pm = (K \nu_0 \pm \nu_0 JS/2) \]
The number of Shiba peaks depends on the atom nature
\[ Mn \rightarrow l = 0,1 \]
\[ Cr \rightarrow l = 0,1,2 \]

Every peak corresponds to a different diffusion channel for the superconducting electrons.

Extremely local effect of the impurities (a few Å)
Yu-Shiba-Rusinov bound states in 2D superconductors

\[ \psi_{\pm}^{3D}(r) = \frac{1}{\sqrt{N}} \frac{\sin(k_F r + \delta^\pm)}{k_F r} e^{-\Delta \sin(\delta^+ - \delta^-) r / \hbar v_F} \]

\[ \psi_{\pm}^{2D}(r) = \frac{1}{\sqrt{N}} \frac{\sin \left( k_F r + \delta^\pm - \frac{\pi}{4} \right)}{\sqrt{k_F r}} e^{-\Delta \sin(\delta^+ - \delta^-) r / \hbar v_F} \]

Lower dimensionality leads to larger extents of YSR bound states
Two-dimensionnal superconductors

Bulk superconductor with 2D electronic structure:
- Lamellar material 2H-NbSe$_2$
- Multi gap BCS
- $T_c \approx 7, 2 \text{ K}$

Ultimately thin superconductor:
- Single atomic layer of Pb/Si(111)
- $T_c \approx 1, 5 \text{ K} - 1, 8 \text{ K}$
- Discovered to be superconducting in 2010

**2H-NbSe$_2$ as a two-dimensional superconductor**

Two-dimensional like bands structure due to the weak Van der Waals interlayer coupling.
Observation of bound states around magnetic impurities in 2H-NbSe₂

The Nb used for the crystal growth contains magnetic impurities:
  - 175 ppm of Fe
  - 54 ppm of Cr
  - 22 ppm of Mn

$dI/dV$ maps at -0.13 mV (320 mK)

Observation of bound states around magnetic impurities in 2H-NbSe$_2$

Shiba bound states observed over scales of the order of 10nm
Distance (nm)

Spatial oscillation of Shiba bound states
Electron-hole asymmetry

- Oscillations of the local density of states with a phase opposition between positive and negative energy states

- Decrease of the Shiba bound states on a size of the order of the coherence length $\xi$
Spatial oscillations and electron-hole asymmetry

Good agreement with theoretical calculations for 2D case in the asymptotic limit.

Two relevant length scales: \( k_F \) & \( \xi \)

The Shiba peaks position relatively to the gap is directly related to the phase shift.

\[
\psi_{\pm}(r) = \frac{1}{\sqrt{N\pi k_F r}} \sin \left( k_F r - \frac{\pi}{4} + \delta^\pm \right) e^{-\Delta \sin(\delta^+ - \delta^-)r/\hbar v_F} \\
E = \Delta \cos(\delta^+ - \delta^-) \\
\tan \delta^\pm = (K \nu_0 \pm \nu_0 JS/2)
\]
Two-dimensionnal superconductors

• Bulk superconductor with 2D electronic structure:
  Lamellar material 2H-NbSe$_2$

• Ultimately thin superconductor:
  Single atomic layer of Pb/Si(111)

Effect of non-magnetic disorder on the superconductivity of a single atomic layer of Pb/Si(111)

Striped-Incommensurate Pb/Si(111), 1.33 monolayer

√3 × √7-Pb/Si(111), 1.2 monolayer

Effect of non-magnetic disorder on the superconductivity on $\sqrt{3} \times \sqrt{7}$-Pb/Si(111)

$\sqrt{3} \times \sqrt{7}$-Pb/Si(111)
1.2 monolayer

Gap filling and fluctuations of zero bias conductance: non conventional superconducting order?

$\xi_{\text{eff}} \sim 45\text{nm}$

C. Brun et al., Nat. Phys. 10, 444 (2014)
Quasiparticle interferences as a fingerprint of triplet superconducting order in $\sqrt{7}\times\sqrt{3}$-Pb/Si(111)

Topographic map of $\sqrt{7}\times\sqrt{3}$-Pb/Si(111)

Conductances map inside the gap

Average conductance spectrum
Quasiparticle interferences as a fingerprint of triplet superconducting order in $\sqrt{7}\times\sqrt{3}$-Pb/Si(111)

Fourier transform of the conductance map at -0.2 mV

Fermi surface related scattering vectors
Quasiparticle interferences as a fingerprint of triplet superconducting order in $\sqrt{7}\times\sqrt{3}$-Pb/Si(111)

Fourier transform of the conductance map at -0.2 mV

Some scattering channels are forbidden: spin selective effect?
Shiba bound states in the stripe incommensurate monolayer of Pb/Si(111)

$\sqrt{7}\times\sqrt{3}$-Pb/Si(111), 1.2 monolayer

Topography

Conductance map at 0 mV

Conductance spectra on top and far from the impurity
Magnetic vs non-magnetic impurities
Signature of a triplet component?

Magnetic impurities

Non magnetic impurities
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Continuous transformation of the system

Break and rebuild the system for this configuration. 2 configurations → 2 topological indices.

Different topology
Trivial vs topologic 1D superconductor

Trivial superconductor

No edge states

Topological superconductor

Majorana zero energy bound state
Majorana end states in a magnetic chain on top of a superconductor Fe/Pb(110)

Stevan Nadj-Perge et al., Science **346**, 6209 (2014)

Vazifeh and Franz, PRL **111**, 206802 (2013)
Nadj-Perge et al, PRB **88**, 020407(R) (2013)
Braunecker and Simon, PRL **111**, 147202 (2013)
Topological transition in a Rashba superconductor in a magnetic field

Free electrons + Rashba spin-orbit coupling + Zeeman

Trivial

Topological transition

Topological
Majorana dispersions at the edge of 2D topological superconductors

- **Trivial superconductor**: No edge states
- **Helical Topological superconductor**: Time reversal symmetric edge states
- **Chiral Topological superconductor**: Majorana edge states dispersion inside the gap

- **Time reversal invariant**
- **Broken time reversal symmetry**

**Examples of edge states dispersion**
Topological superconductivity: Chiral vs Helical

\[ H = \xi_k \tau_z + \Delta_S \tau_x + V_Z \sigma_z + \alpha \tau_z \]

Rashba + Zeeman splitting \( V \)

Broken time reversal

1 chiral edge state

\[ H = \xi_k \tau_z + \Delta_S \tau_x + \frac{\Delta_T}{k_F} \tau_x (\sigma_x k_y - \sigma_y k_x) \]

\( \Delta_T \) is a time reversal symmetric triplet pairing

2 helical edge states

equivalent by time reversal
Topological superconductivity: Chiral vs Helical

\[ H = \xi k\tau_z + V_Z\sigma_z + \alpha\tau_z + \Delta_S\tau_x + \frac{\Delta_T}{k_F}\tau_x(\sigma_xk_y - \sigma_yk_x) \]

Two control parameters:
- Zeeman field
- Triplet amplitude

Two topological regimes:
- Chiral (one edge states) \(\equiv\) quantum Hall effect
- Helical (two edge states) \(\equiv\) quantum spin Hall effect

Topological superconductivity: Chiral vs Helical

\[
H = \xi_k \tau_z + V_Z \sigma_z + \alpha \tau_z + \Delta_S \tau_x + \frac{\Delta_T}{k_F} \tau_x (\sigma_x k_y - \sigma_y k_x)
\]

Towards 2D topological superconductivity

Pb/Si(111) Rashba superconductor coupled to a ferromagnetic domain
Edge states around magnetic nanodomain in Pb/Co/Si(111)

Observation of perfectly circular structure at the Fermi energy around buried Co clusters

300 mK conductance map at $E_F$ using a superconducting tip

Splitting of helical edge states due to broken time reversal

Majorana dispersions in Pb/Co/Si(111)

Cross section of a Majorana edge states dispersion
Theoretical modelling of Majorana dispersion

Slowly varying magnetic field defining a chiral area surrounding by a trivial area on top of singlet-triplet mixed superconductor with Rashba spin-orbit interaction

Majorana bound states

Majorana dispersive states are fine but braiding experiments require Majorana zero energy bound states

How to obtain Majorana bound states with a 2D topological superconductor?

Vortex
Majorana bound state in a vortex core
Conclusion

Role of dimensionality and Fermi surface for Shiba bound states

Topological superconductivity induced by a ferromagnetic domain

Hybrid helical-chiral topological state

Majorana zero-energy bound states in vortex cores
Thank you!