STM study of topological superconductivity in Pb/Si(111)

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Plan

I. STM-STS & superconductivity - Magnetic impurities in superconductors

II. Individual magnetic impurities in Pb/Si(111)

III. Topological superconductivity

IV. Majorna edge states and bound states.

V. Conclusion
STM & Yu-Shiba-Rusinov bound states
Yu-Shiba-Rusinov bound states

Cooper pairs split under a Zeeman field

\[ \hat{H}_{\text{BCS}} = \Delta \hat{c}_{k,\uparrow} \hat{c}_{-k,\downarrow} + \text{h.c.} \]

\[ \hat{H}_{\text{mag}} = J \hat{\sigma}_z \cdot \vec{S} \]

The number of states depends on the spatial extension of the interaction. For a point defect, only one pair of Shiba states will appear within the gap.
Yu-Shiba-Rusinov bound states

First STM measurement of YSR bound states.

S.-H. Ji et al. PRL 100 226801 (2008)
Magnetic impurities in Pb/Si(111)
Monolayer of Pb/Si(111)

There exists different superconducting phases in monolayer Pb/Si(111)

Example of bound states in Pb/Si(111)

Case of the SIC phase and $\sqrt{7} \times \sqrt{3}$

Example of bound state (NbSe2)

Imaging of a single Fe atom embedded in 2H-NbSe2

The dephasing between the electron & hole like state is linked to the relation between the gap, the magnetic interaction and the non magnetic interaction.

Furthermore, using a 2D material increases by order of magnitude the extent of the wavefunction associated with the YSR bound states.

Topological superconductors
Topography & solid state physics

3 ingredients are required for topological superconductivity:

- Superconductivity
- Spin orbit interaction
- Magnetism

These are provided by:

- Electron phonon interaction
- Surface effect/Heavy element
- Magnetic atoms/External field
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The edge state associated to topological superconductivity is called a **Majorana fermion**.

They are anyons that possesses non Abelian statistics.
Previous observations of ZBP


S. Nadj-Perge et al. 346 602-607 Science (2014)
Majorana edge states & Majorana bound states in Pb/Co/Si(111)
Theory of Majorana edge states

\[ \hat{H}_0 = \xi \tau_z + \Delta \tau_x \]

Trivial superconductor

\[ \hat{H}_{\text{topo}} = V_z \sigma_z + \left( \alpha \tau_z + \frac{\Delta_T}{k_F} \tau_x \right) (\sigma_x k_y - \sigma_y k_x) \]

Triplet superconductivity & Spin-orbit interaction

Magnetic interaction
A spatially varying magnetic field in a triplet superconductor can induce a topological transition in space.
Topological Majorana edge states

High bias surface topography

Low bias spectroscopy (using superconducting tip)

Topological Majorana edge states

Topological Majorana edge states

What shows up as a perfect ring at zero energy splits at finite bias into two well separated structures.

By taking a cut through the center of the cluster we can image the spatial dispersion of the topological edge band.

Theory of Majorana bound states

We take the Hamiltonian that was previously used adding a vortex term in the spin-orbit coupling such that

$$\hat{H} = \int d^2 r \Psi_{\vec{r}}^\dagger \left[ ( - \eta \nabla^2 - \mu ) \tau_z + \Delta S \tau_x + V_z(\vec{r}) \sigma_z \right] \Psi_{\vec{r}} + H_{SO-defect}(\vec{r})$$

$$\hat{H}_{SO-defect}(\vec{r}) = \hat{c}_{\vec{r}\uparrow}^{\dagger} \left\{ \alpha e^{i\theta(\vec{r})}, \nabla_x - i \nabla_y \right\} \hat{c}_{\vec{r}\downarrow} + h.c.$$
Theory of Majorana bound states

From a continuum of state we now only have one pair of well-separated zero-bias states within the gap

\[
\hat{H} = \int d^2 r \Psi^\dagger_\vec{r} \left[ (-\eta \nabla^2 - \mu)\tau_z + \Delta_S \tau_x + V_z(\vec{r})\sigma_z \right] \Psi_{\vec{r}} + H_{SO-defect}(\vec{r})
\]

\[
\hat{H}_{SO-defect}(\vec{r}) = \hat{c}^\dagger_{\vec{r}\uparrow} \left\{ \alpha e^{i\theta(\vec{r})}, \nabla_x - i \nabla_y \right\} \hat{c}_{\vec{r}\downarrow} + h.c.
\]

Superconductivity

Magnetic interaction

Spin-orbit interaction with vortex in phase

Topological Majorana bound states

Slightly changing the amount of Co on the surface changes the size of the cluster and zero bias peak can be observed at the center of magnetic clusters.

Conclusion

* We measured individual impurities in a variety of phases

* We grew disordered nano clusters of Co buried under Pb on a Si(111) substrate and observed YSR bands.

* We grew ordered nanoclusters and observed topological edge states

* In slightly different configuration we observed disorder-proof zero-bias peaks
Collaborators

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Theory team in LPS:
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Thank you for your attention