From single magnetic adatoms to coupled chains on a superconductor
Magnetic adatoms on a superconductor

Mn adatom on Pb(111)

40 mV, 40 pA

▶ classical spins exchange scatter at a magnetic center:

\[
\epsilon_0 = \frac{E_0}{\Delta_0} = \frac{1 - (JS\pi N_0/2)^2}{1 + (JS\pi N_0/2)^2}
\]

▶ Yu-Shiba-Rusinov states

A.I. Rusinov, JETP Lett. 9, 85 (1969)
Magnetic adatoms on a superconductor

- transport through Shiba states?
- origin of multiple Shiba states?
Magnetic adatoms on a superconductor

- transport through Shiba states?
- origin of multiple Shiba states?
- formation of Shiba bands?
- topological states?
Outline

Single atoms: Mn on Pb(111) and Pb(100)
- Transport mechanisms through Shiba states?
- Multiple Shiba states

Atomic chains: Co on Pb(110)
- Shiba bands and Majorana states?
Impurity induced bound states

- Shiba states of Mn atoms on Nb(111) (T=4 K)

  ![Graph A](image1.png)

  Yazdani et al, Science 275, 1767 (1997)

- Shiba states of Mn atoms on Pb(111) (T=0.3 K)

  ![Graph B](image2.png)

  Ji et al, PRL 100, 226801 (2008)

- Shiba states interpreted in single electron tunneling picture

- Shiba height reflects amplitude of electron/hole Shiba wavefunction
Mn atoms on Pb(111)

- multiple Shiba resonances
- asymmetric peak heights
Mn atoms on Pb(111)

- BCS peaks
- multiple Shiba resonances
- thermally excited Shiba states
Shiba states at different junction conductances

- symmetry of Shiba intensity varies with junction conductance
- intensity cannot be interpreted as density of states

Shiba states at different junction conductances

Low junction conductance:
- single particle current
- tunneling into Shiba state changes occupancy
- relaxation necessary

\[ I^S \propto t^2 \Gamma_1 \]

Shiba states at different junction conductances

- sublinear increase of Shiba state conductance at high tunnel rates
- inversion of Shiba intensity

Shiba states at different junction conductances

- Sublinear increase of Shiba state conductance at high tunnel rates
- Inversion of Shiba intensity
- Higher temperatures: crossover at larger tunnel rates
- Thermally activated relaxation

Lifetimes:
- 0.2 ns at 1.2 K
- 6 ps at 4.8 K
Mn/Pb(001)

three Shiba states of Mn atoms


Origin of multiple Shiba states

► characteristic shape of Shiba states resembles d-orbitals

Mn/Pb(111)

- different adsorption sites yield different Shiba splittings
- crystal field splitting

Pb(111): shape and extension of Shiba states

► all degeneracies lifted

► crystal field splitting:

\[ \frac{dI}{dV} \text{ maps, } 8.8 \times 8.8 \text{ nm}^2 \]

\[ d_{xy}, x^2 - y^2 \]
\[ d_{xz}, yz \]
\[ d_{z^2} \]

Shape and extension of Shiba states

- maps reflect symmetry of singly occupied states
- extension?

\[
\psi^\pm(r) \propto \frac{\sin(k_F r + \delta^\pm)}{k_F r} \exp \left[ -|\sin(\delta^+ - \delta^-)| \frac{r}{\xi} \right]
\]

\[
\epsilon = \Delta \cos(\delta^+ - \delta^-)
\]
Shape and extension of Shiba states

- oscillation with the Fermi wave length / 2
- phase shift between negative and positive energy

$$\psi^\pm(r) \propto \frac{\sin(k_F r + \delta^\pm)}{k_F r} \exp \left[ -|\sin(\delta^+ - \delta^-)| \left| \frac{r}{\xi} \right| \right]$$

- anisoptric scattering due to anisotropic Fermi surface
- identification of Fermi sheet

Outline

- Single atoms: Mn on Pb(111) and Pb(100)
  - Transport mechanisms through Shiba states?
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- Atomic chains: Co on Pb(110)
  - Shiba bands and Majorana states?
Toy model: Kitaev chain

1D chain of atomic sites

- single Majorana operators at the chain ends

- conditions for the topological state:
  - spin-less bands along the chain
  - superconductivity within the chain
Transition metal chains on Pb(110)

- Concept:
  - Couple a ferromagnetic chain to a superconductor with spin-orbit coupling

- p-wave superconductivity by proximity

- Transition metal chains on Pb(110)
Sub-gap structure in Fe chains

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

- Peak at zero bias
- Localized at chain end
- Interpretation as Majorana states
- Topological gap 200-300 µeV
Sub-gap structure in Fe chains

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Co chains on Pb(110): ferromagnetism

- check for ferromagnetism with spin-polarized tips
- spin-polarized d-bands
- ferromagnetic coupling

Co chain on Pb(110): Shiba bands

check for Shiba bands with spin-polarized tips

spin-polarized Shiba-bands

Co chains on Pb(110)

► check for superconductivity within the chain

► signatures for a topological gap observed?

Co chains on Pb(110): high resolution subgap structure

- peaks/shoulders close to zero energy
- chains look similar: 2.5-9.4 nm length

Co chains on Pb(110): localization of states

► Conductance maps

5 mV 1.36 mV 1.45 mV 1.70 mV 1.93 mV 2.31 mV 2.69 mV

zero-energy

► Homogenous distribution of zero-energy signal
  ► No sign of Majorana modes
  ► Why are Fe and Co different?

Band structure of Co chains

without spin-orbit coupling

with spin-orbit coupling

► # crossings at $E_F$:

Fe could have *odd* number of Fermi points

Co could have *even* number of Fermi points
Conclusions

- Two transport mechanisms through Shiba states:
  - Single electron tunneling
  - Resonant Andreev reflections
  - Thermal relaxation from Shiba states

- Shiba states of single atoms:
  - d-level character

- Rich subgap structure on proximity coupled chains
  - Co chains do not show localized zero-energy modes
Thanks!

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