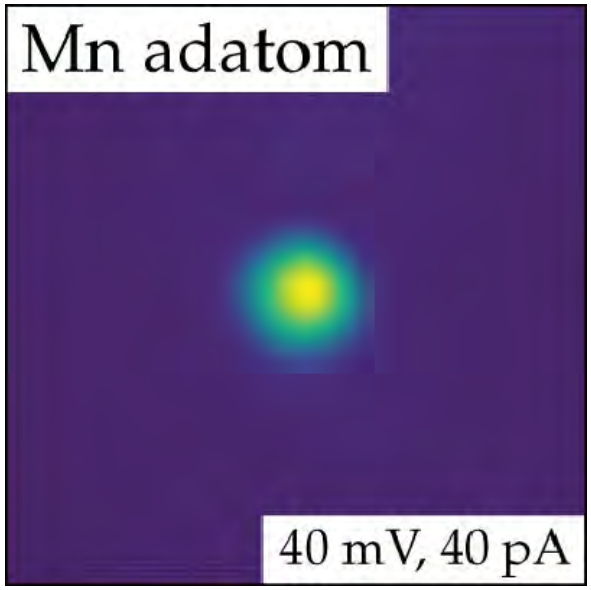
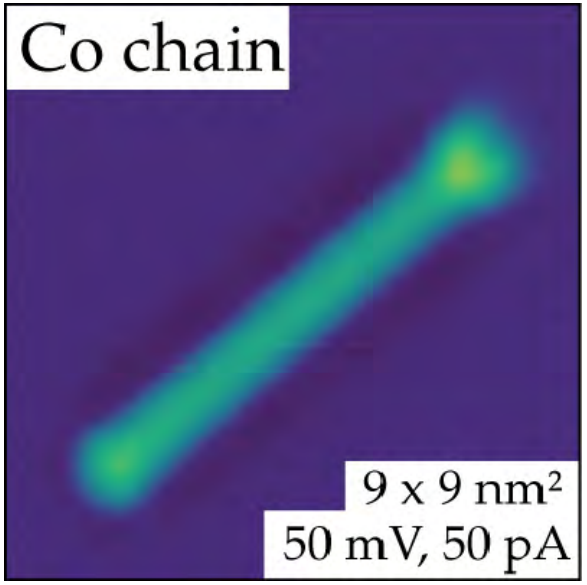
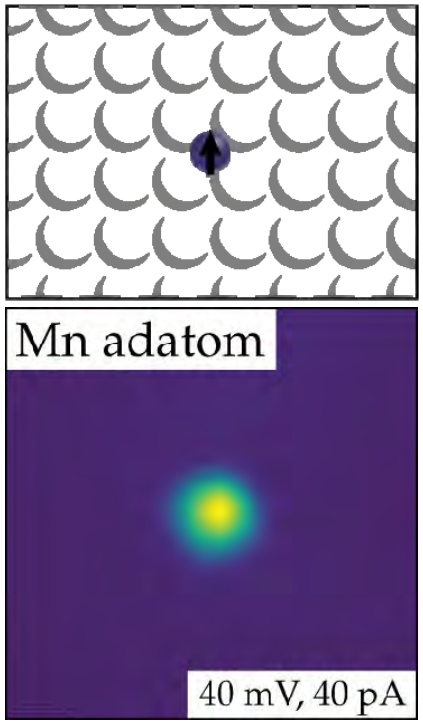
From single magnetic adatoms to coupled chains on a superconductor

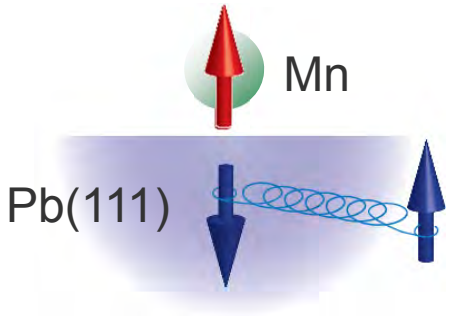


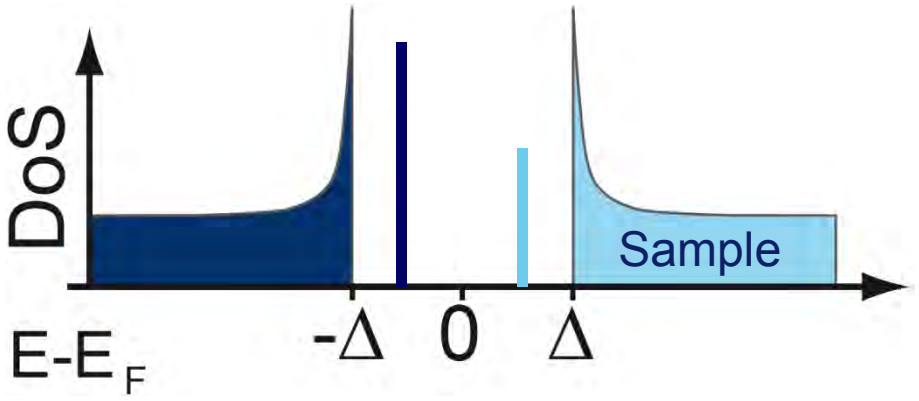


Michael Ruby, Benjamin Heinrich, Yang Peng, Falko Pientka,
Felix von Oppen, Katharina Franke

Magnetic adatoms on a superconductor







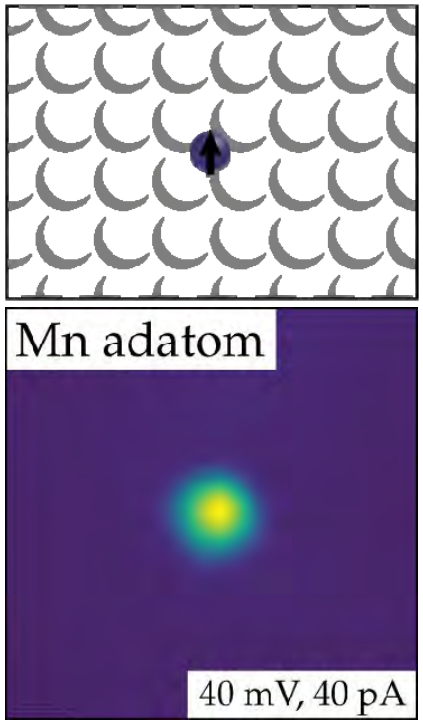
- classical spins exchange scatter at a magnetic center:

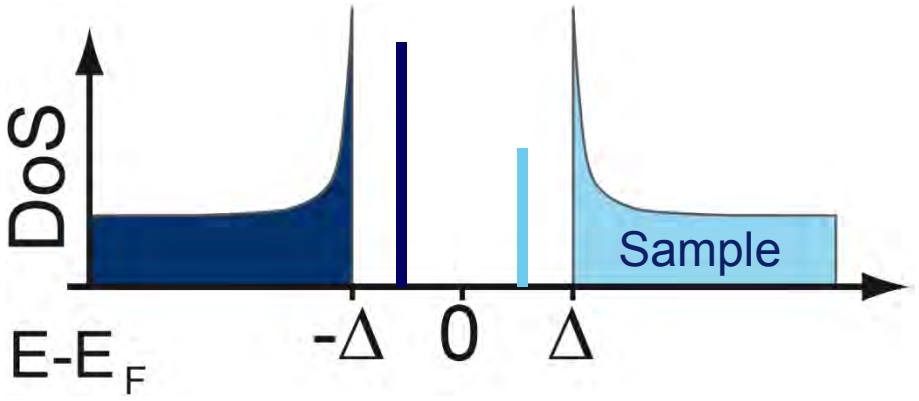
$$\epsilon_0 = \frac{E_0}{\Delta_0} = \frac{1-(JS\pi N_0/2)^2}{1+(JS\pi N_0/2)^2}$$

- Yu-Shiba-Rusinov states

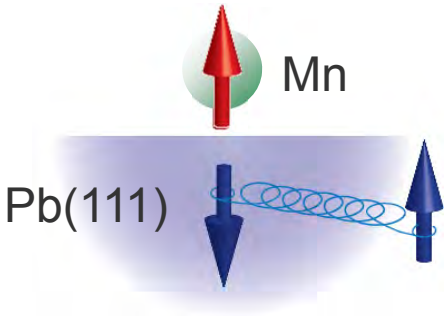
L. Yu, Acta Phys. Sin. 21, 75 (1965)
H. Shiba, Prog. Theor. Phys. 40, 435 (1968)
A.I. Rusinov, JETP Lett. 9, 85 (1969)

Magnetic adatoms on a superconductor

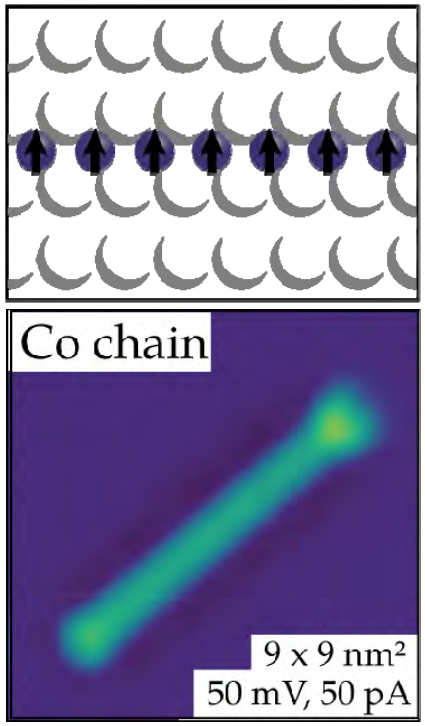


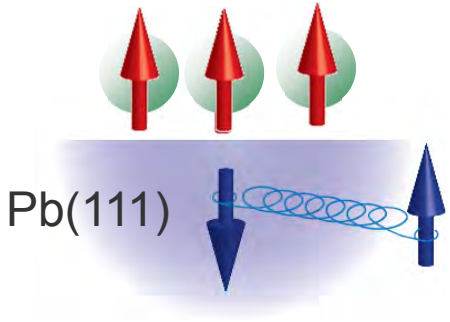


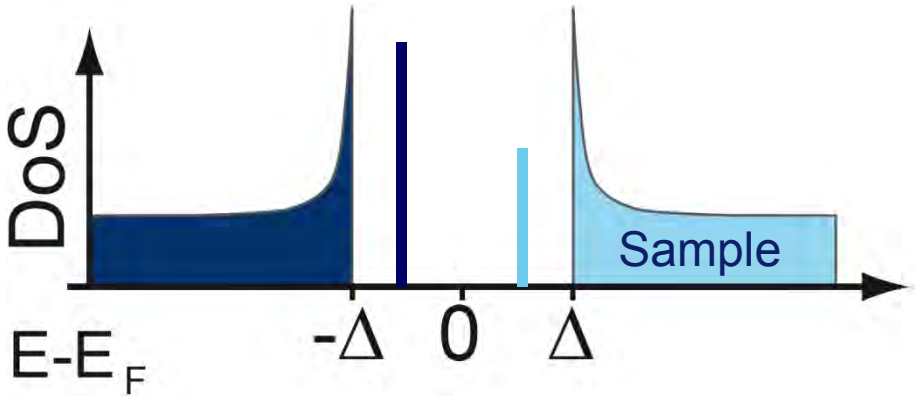
- transport through Shiba states?
- origin of multiple Shiba states?



Magnetic adatoms on a superconductor

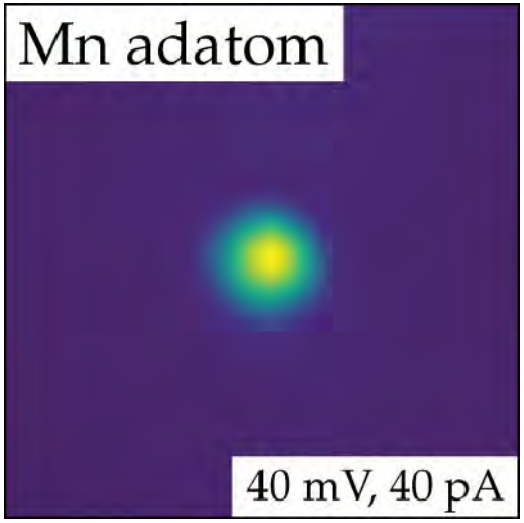






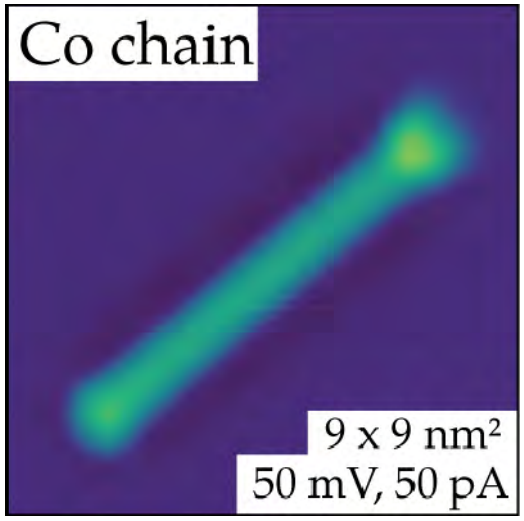
- transport through Shiba states?
- origin of multiple Shiba states?
- formation of Shiba bands?
- topological states?

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

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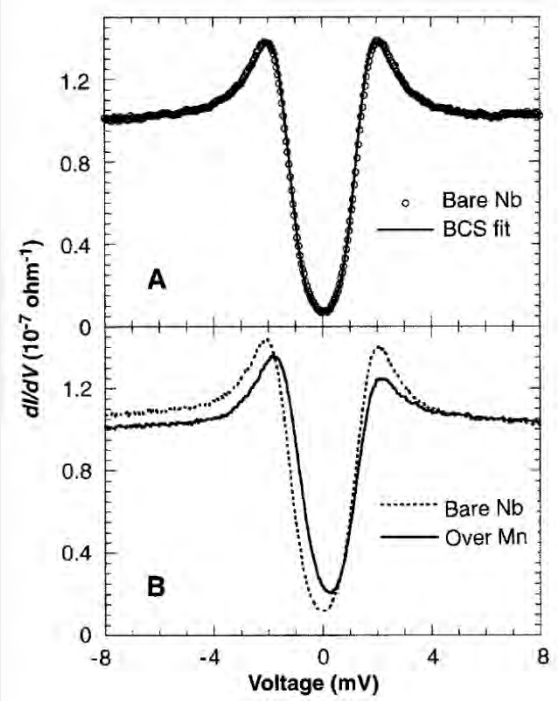
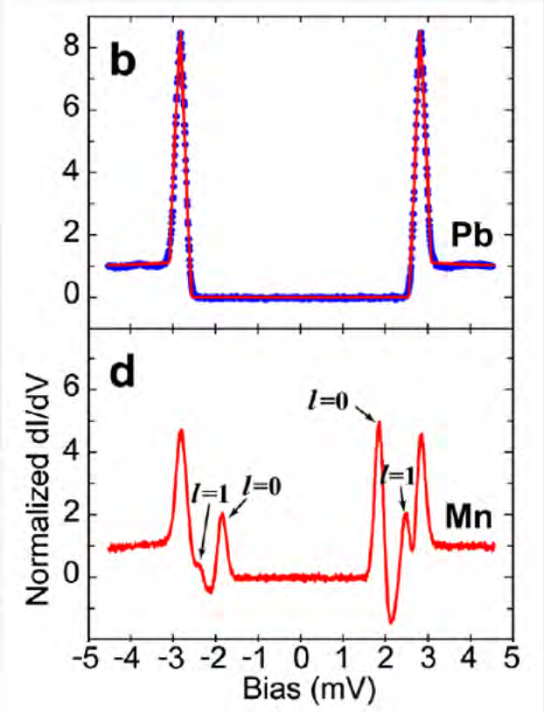
- Shiba states of Mn atoms on Nb(111) (T=4 K)



Yazdani et al, Science 275, 1767 (1997)

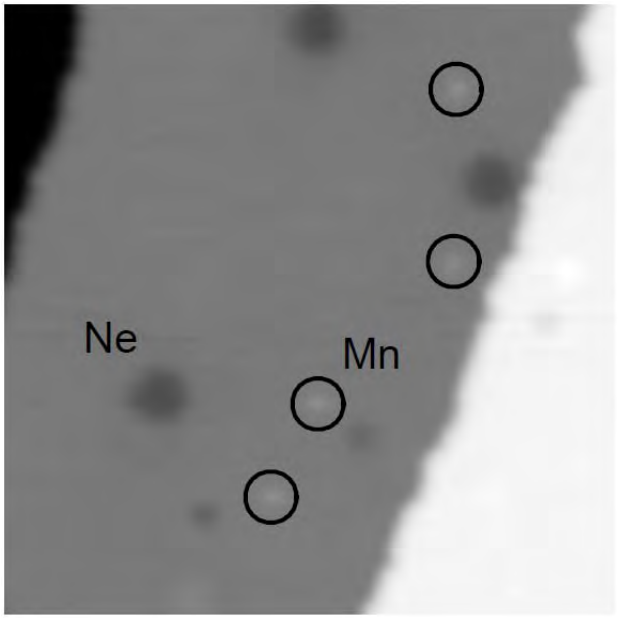
- Shiba states of Mn atoms on Pb(111) (T=0.3 K)

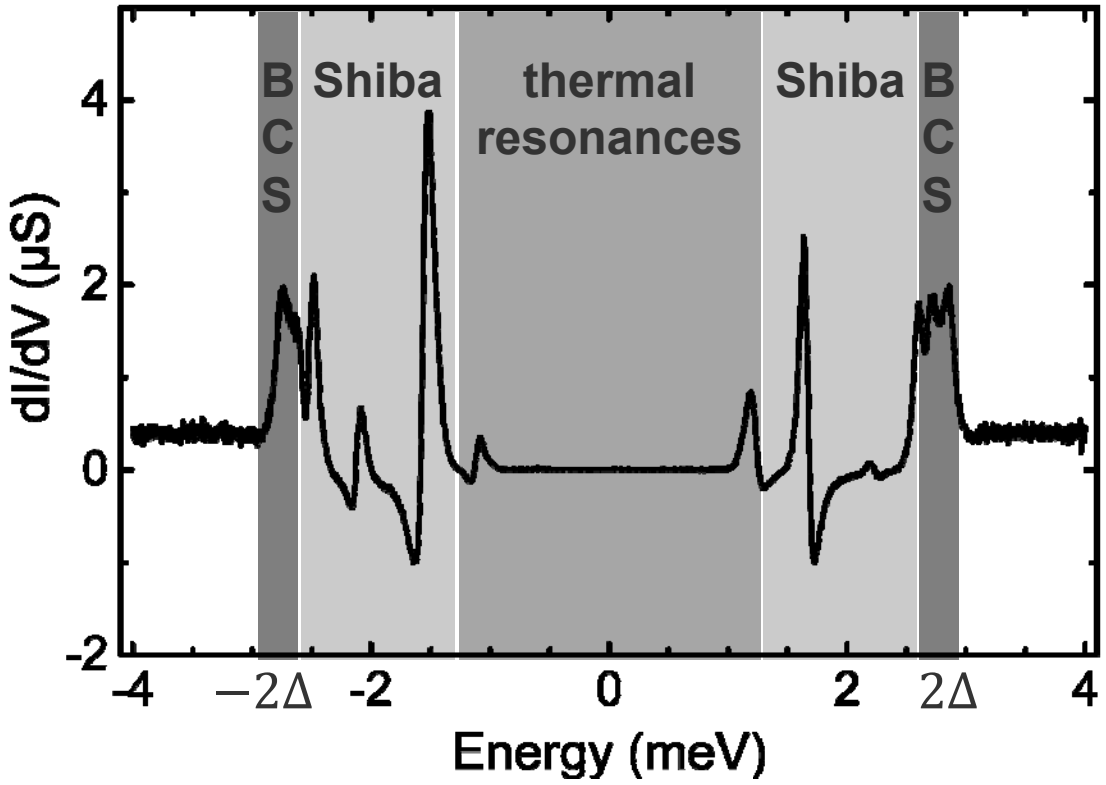


Ji et al, PRL 100, 226801 (2008)

- Shiba states interpreted in single electron tunneling picture
- Shiba height reflects amplitude of electron/hole Shiba wavefunction

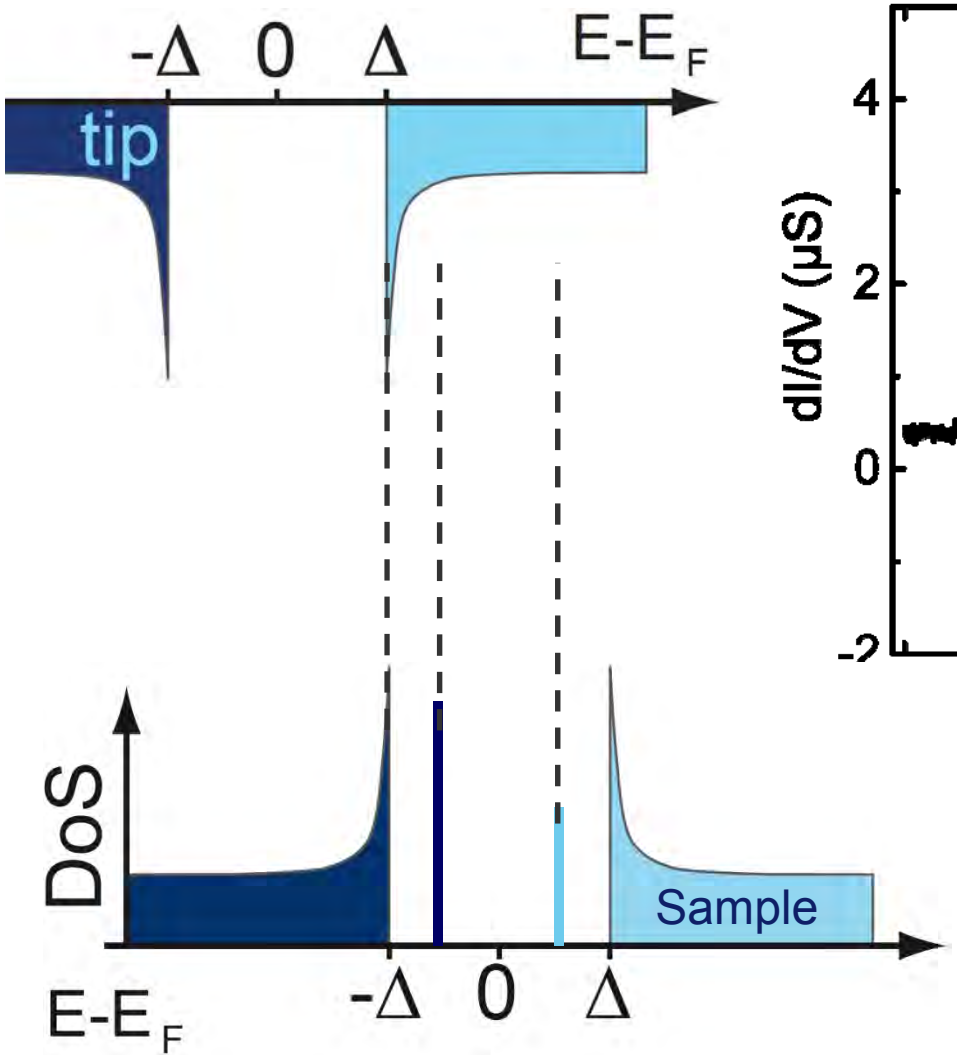
Mn atoms on Pb(111)

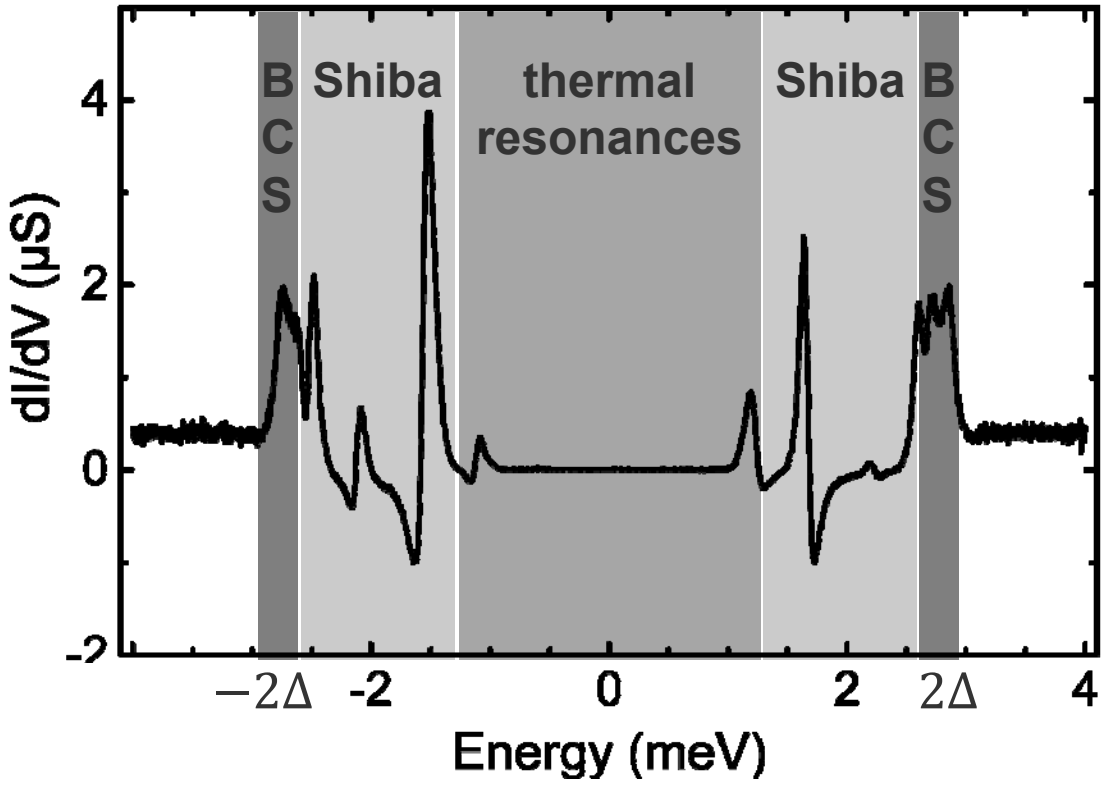




- multiple Shiba resonances
- asymmetric peak heights

Mn atoms on Pb(111)





- BCS peaks
- multiple Shiba resonances
- thermally excited Shiba states

Shiba states at different junction conductances

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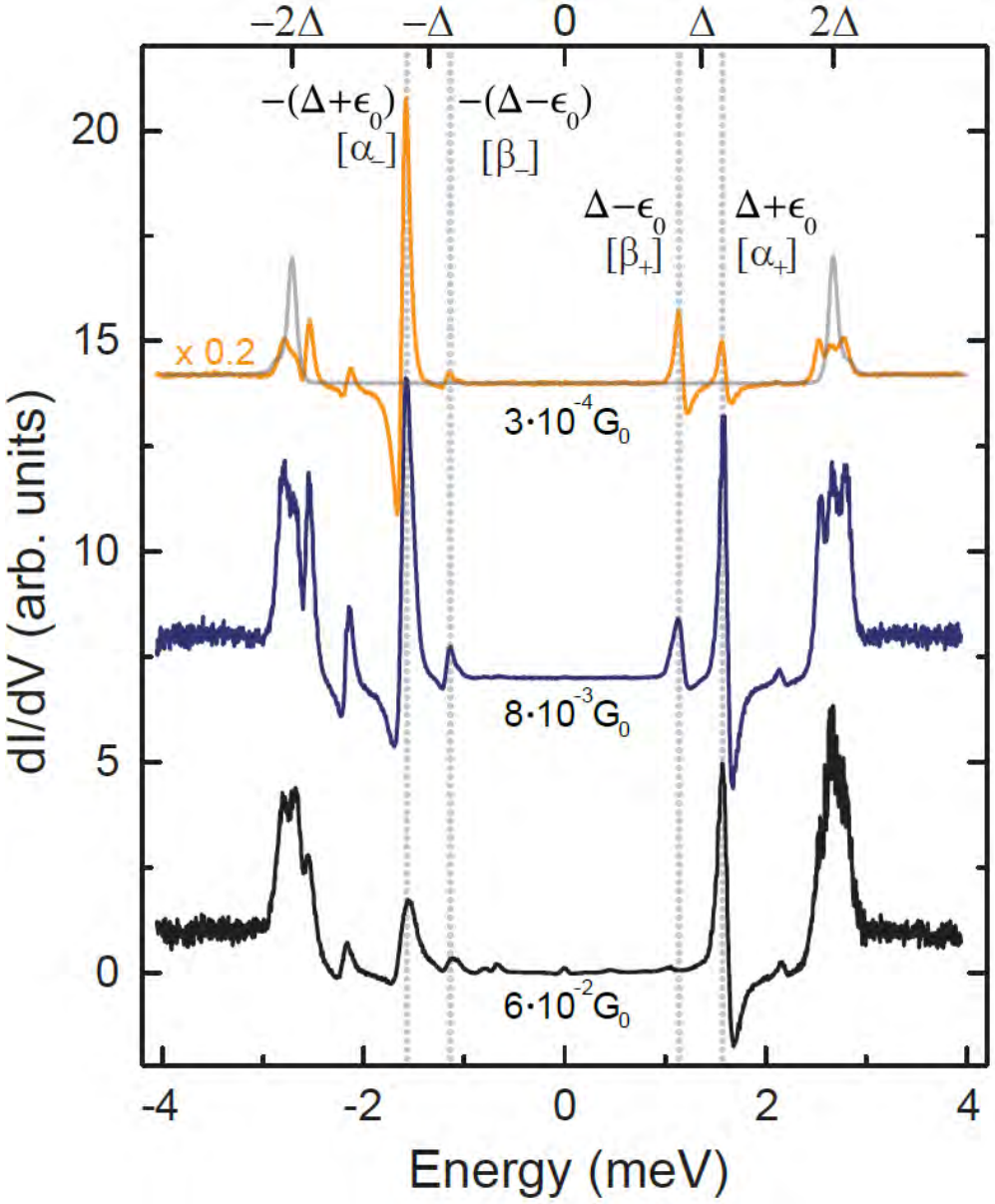
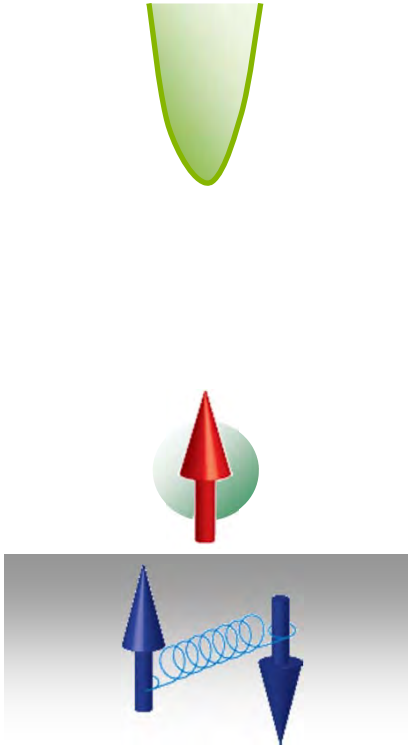
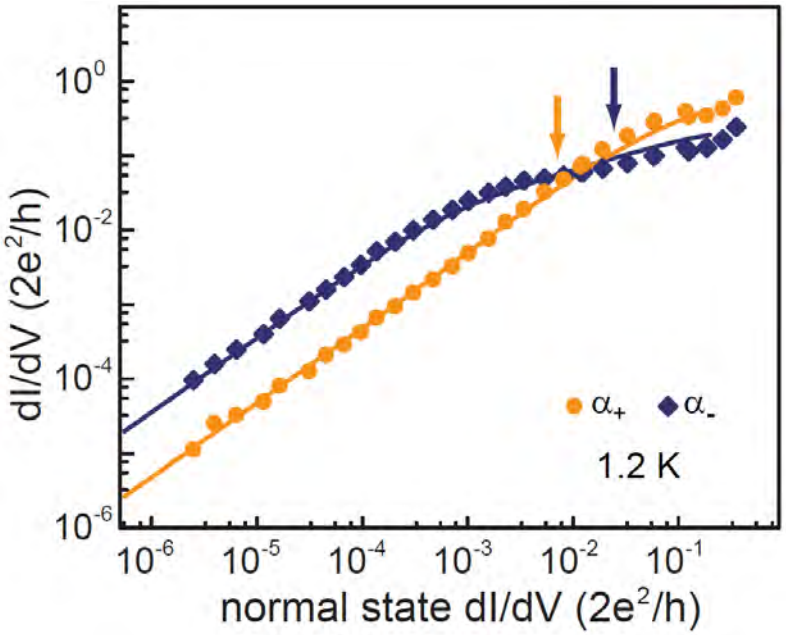


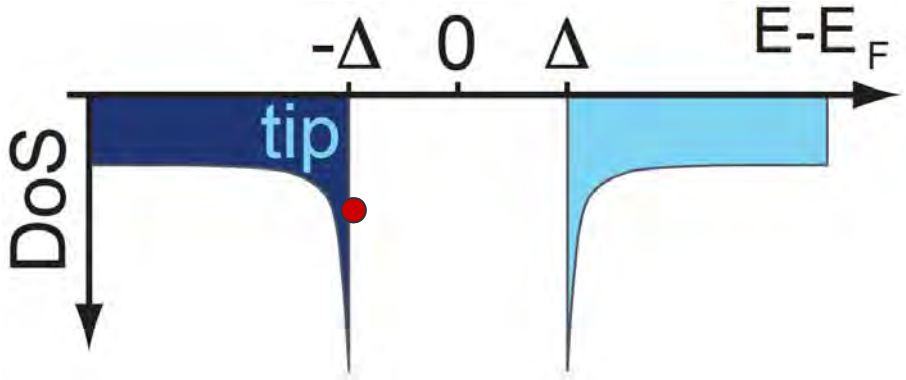


- symmetry of Shiba intensity varies with junction conductance
- intensity cannot be interpreted as density of states

M. Ruby, et al., Phys. Rev. Lett. 115, 087001 (2015)

Shiba states at different junction conductances

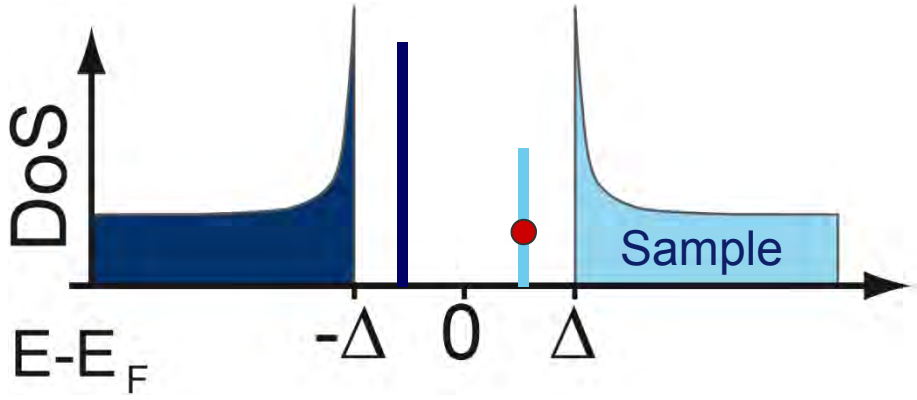




Low junction conductance:

- single particle current
- tunneling into Shiba state changes occupancy
- relaxation necessary

$$I^s \propto t^2 \, \Gamma_1$$



M. Ruby, et al., Phys. Rev. Lett. 115, 087001 (2015)

Shiba states at different junction conductances

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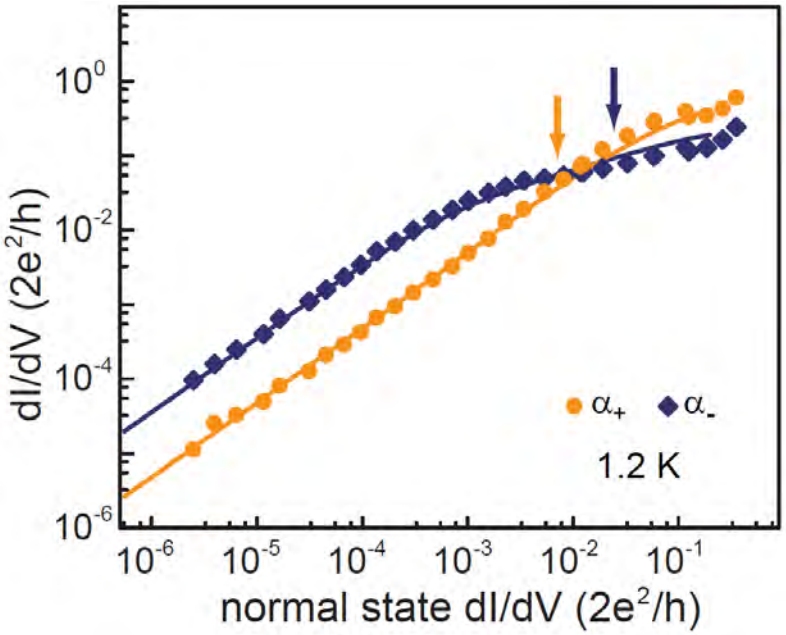
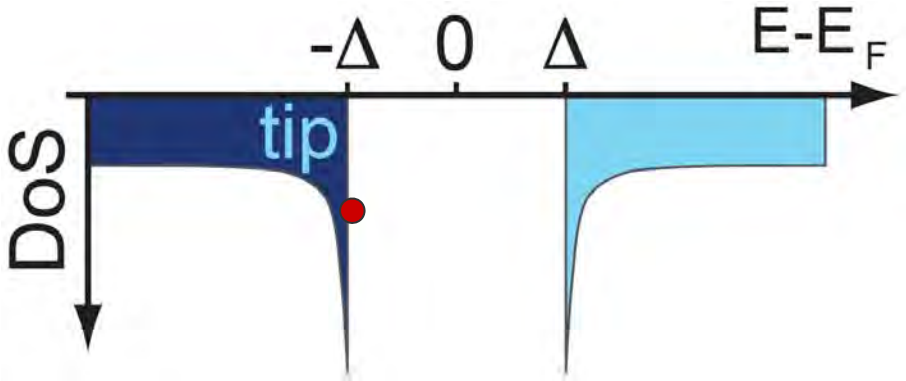
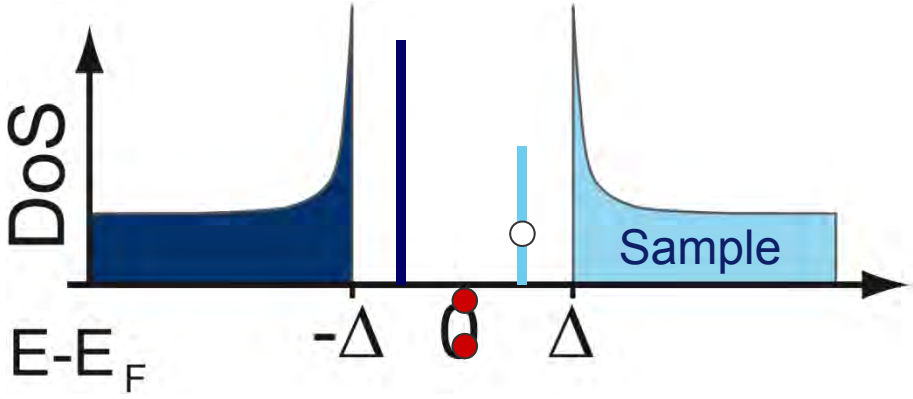




- sublinear increase of Shiba state conductance at high tunnel rates
- inversion of Shiba intensity



M. Ruby, et al., Phys. Rev. Lett. 115, 087001 (2015)

Shiba states at different junction conductances

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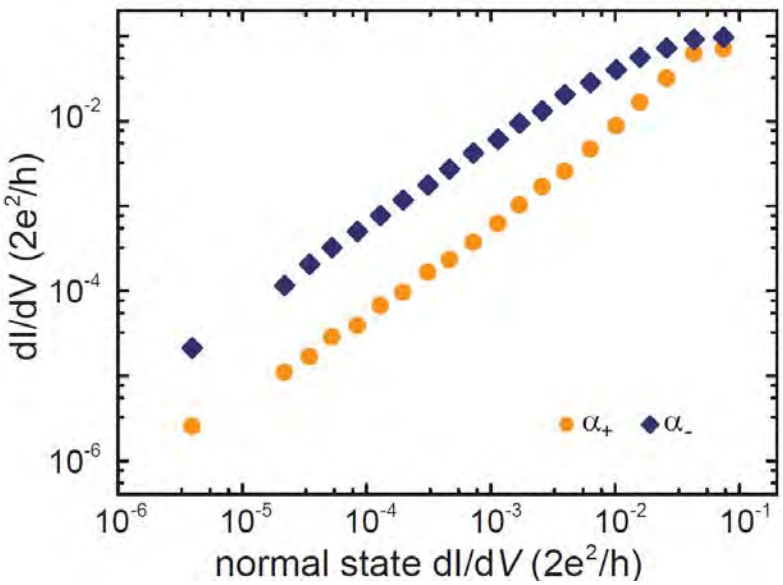
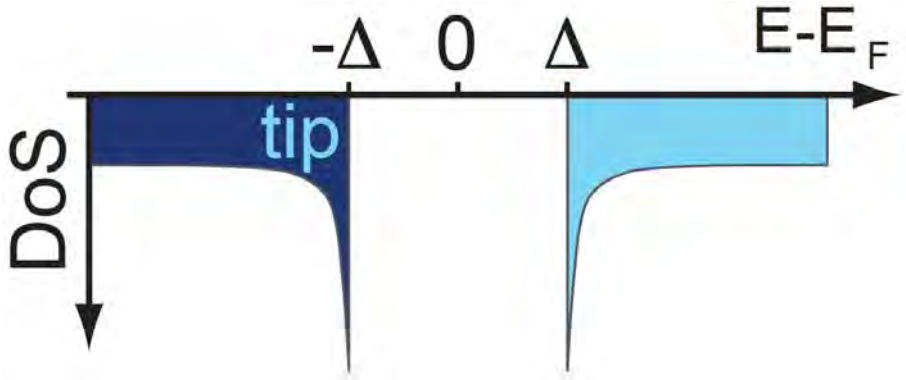
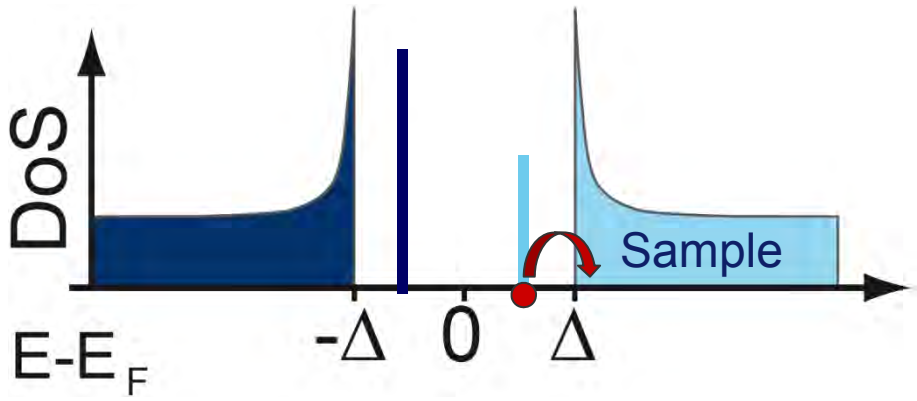




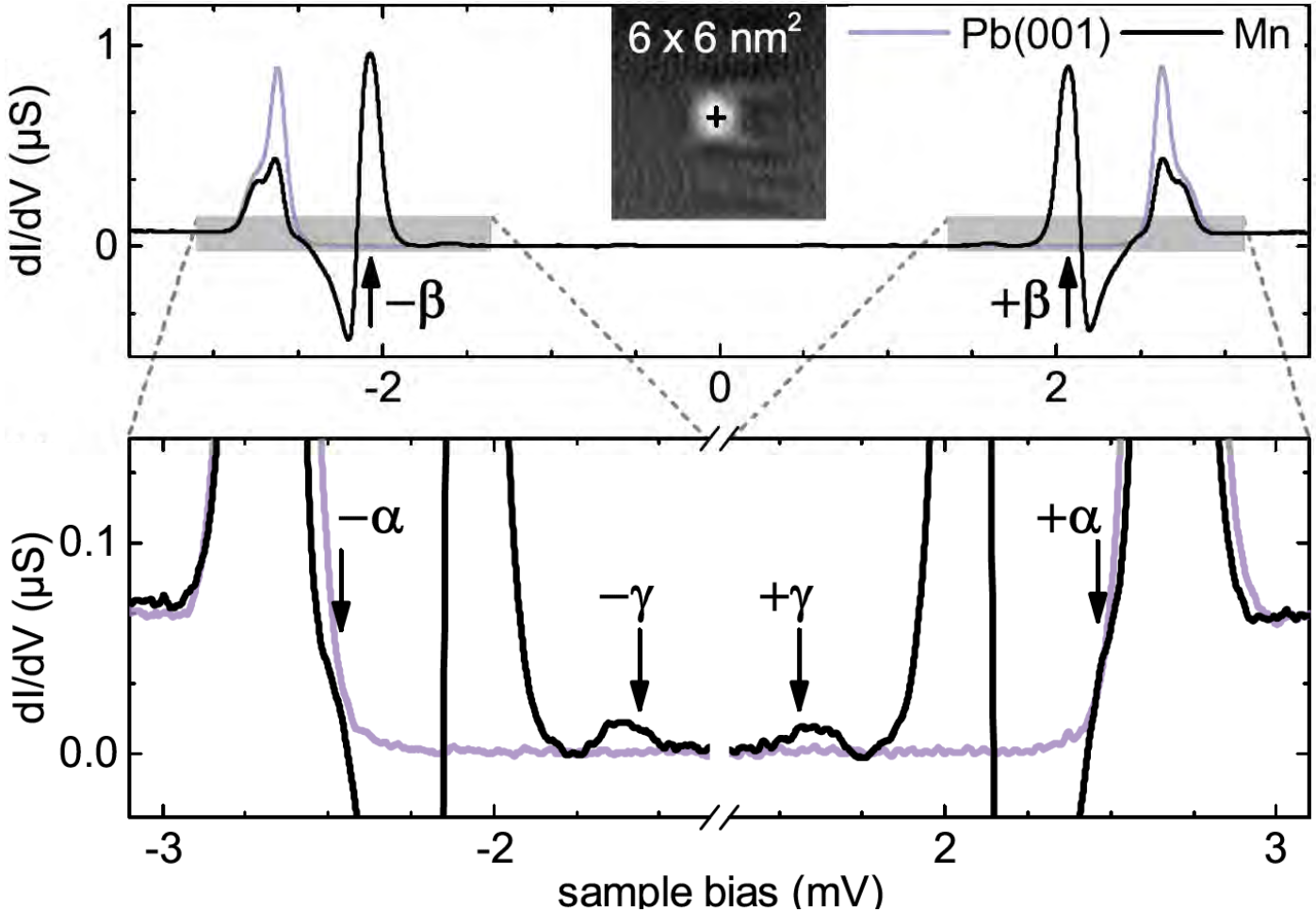


- sublinear increase of Shiba state conductance at high tunnel rates
- inversion of Shiba intensity
- higher temperatures: cross over at larger tunnel rates
- thermally activated relaxation

Theory: Pientka, Peng, von Oppen

Lifetimes: 0.2 ns at 1.2 K
6 ps at 4.8 K

Mn/Pb(001)

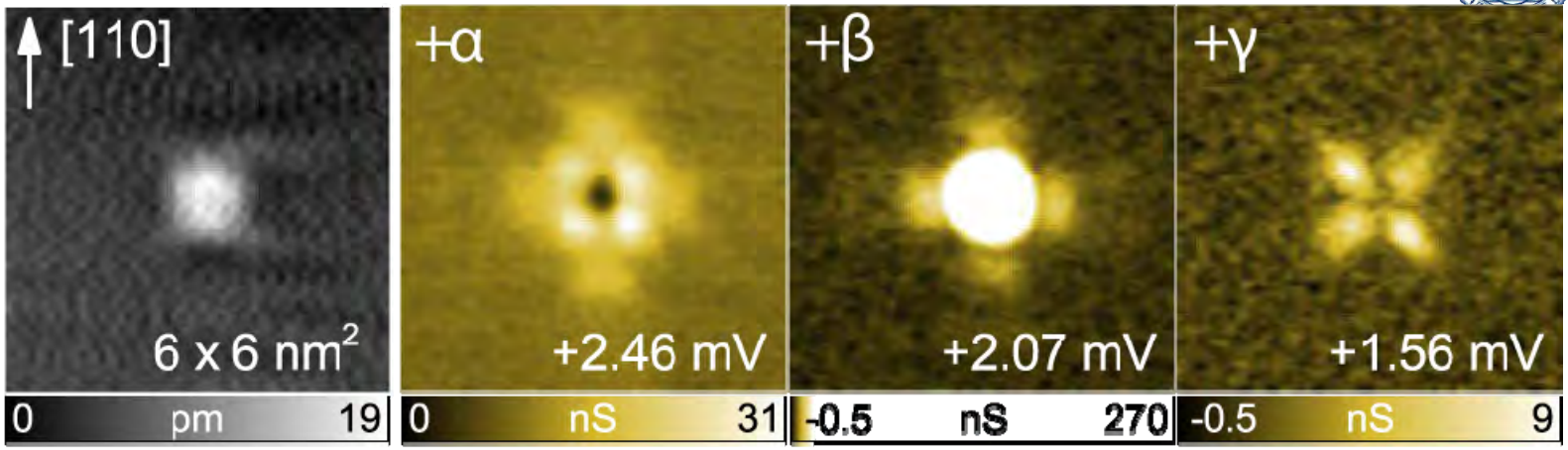


- three Shiba states of Mn atoms

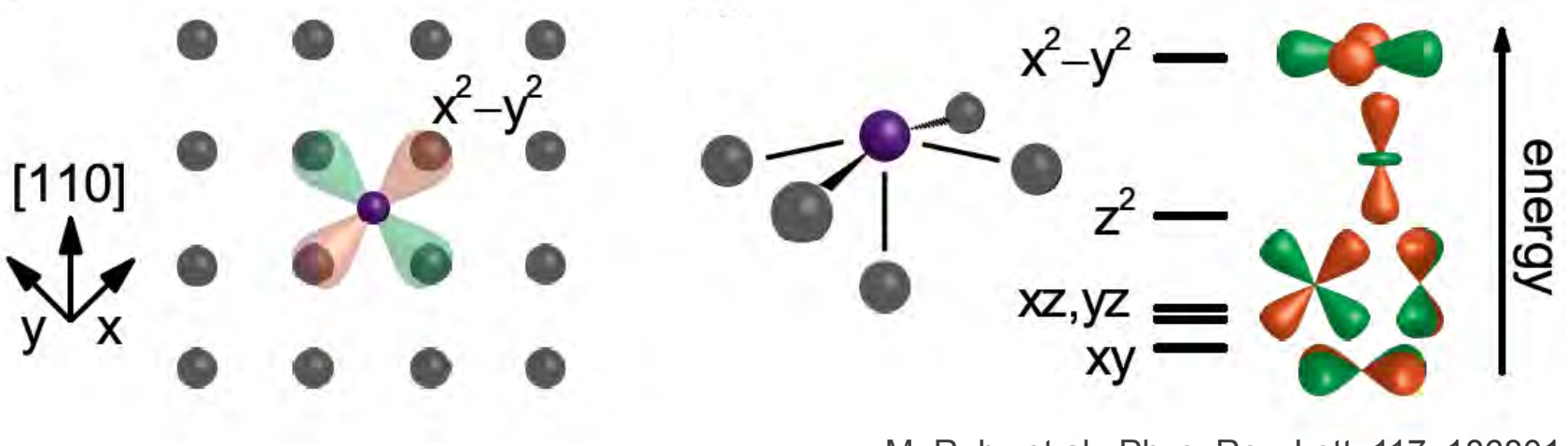
M. Ruby et al., Phys. Rev. Lett. 117, 186801 (2016)

Related: Choi, et al., arXiv:1608.03752 (2016)

Origin of multiple Shiba states

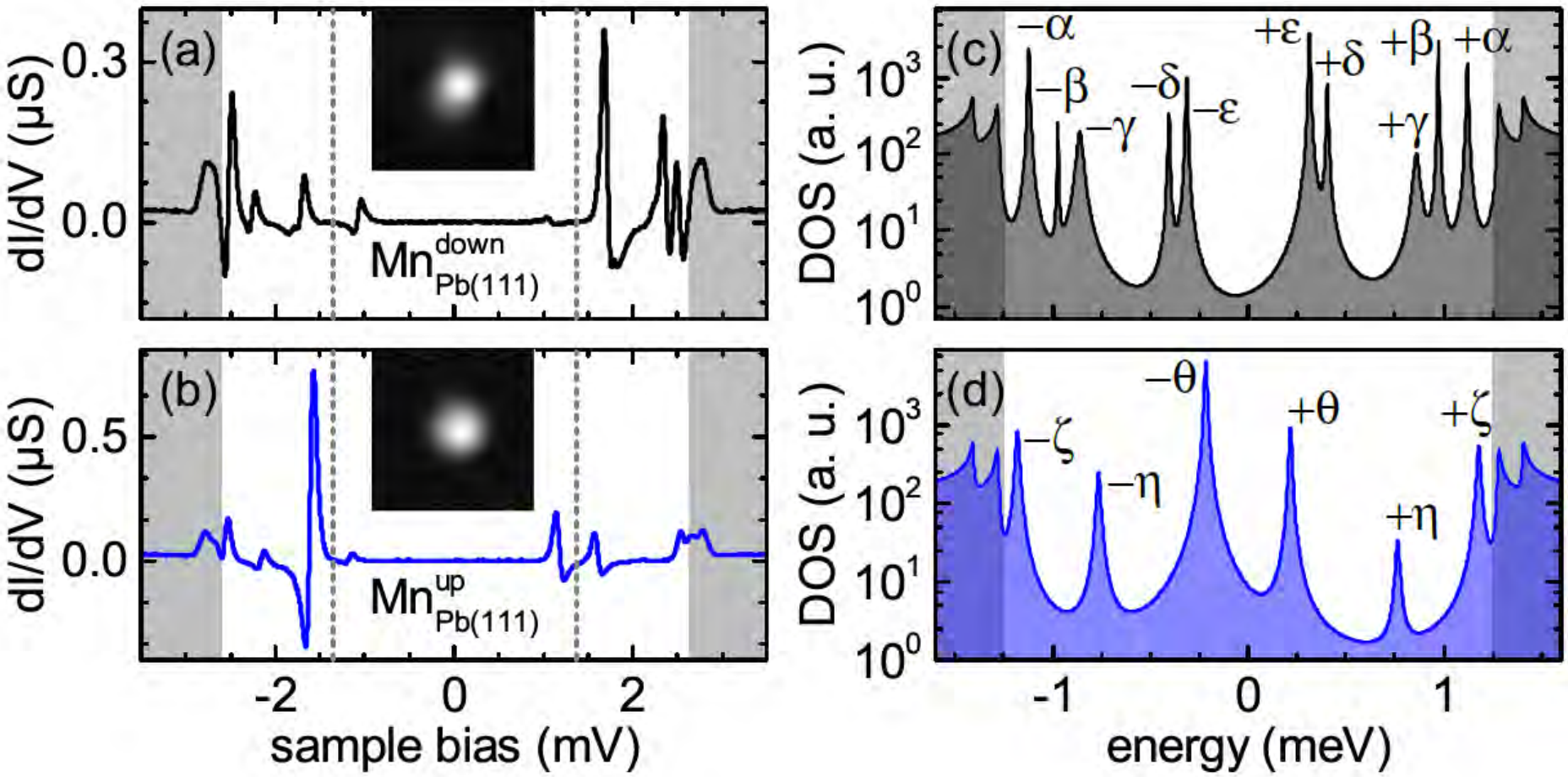


- characteristic shape of Shiba states resembles d-orbitals



M. Ruby et al., Phys. Rev. Lett. 117, 186801 (2016)

Mn/Pb(111)



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

M. Ruby et al., Phys. Rev. Lett. 117, 186801 (2016)

Pb(111): shape and extension of Shiba states

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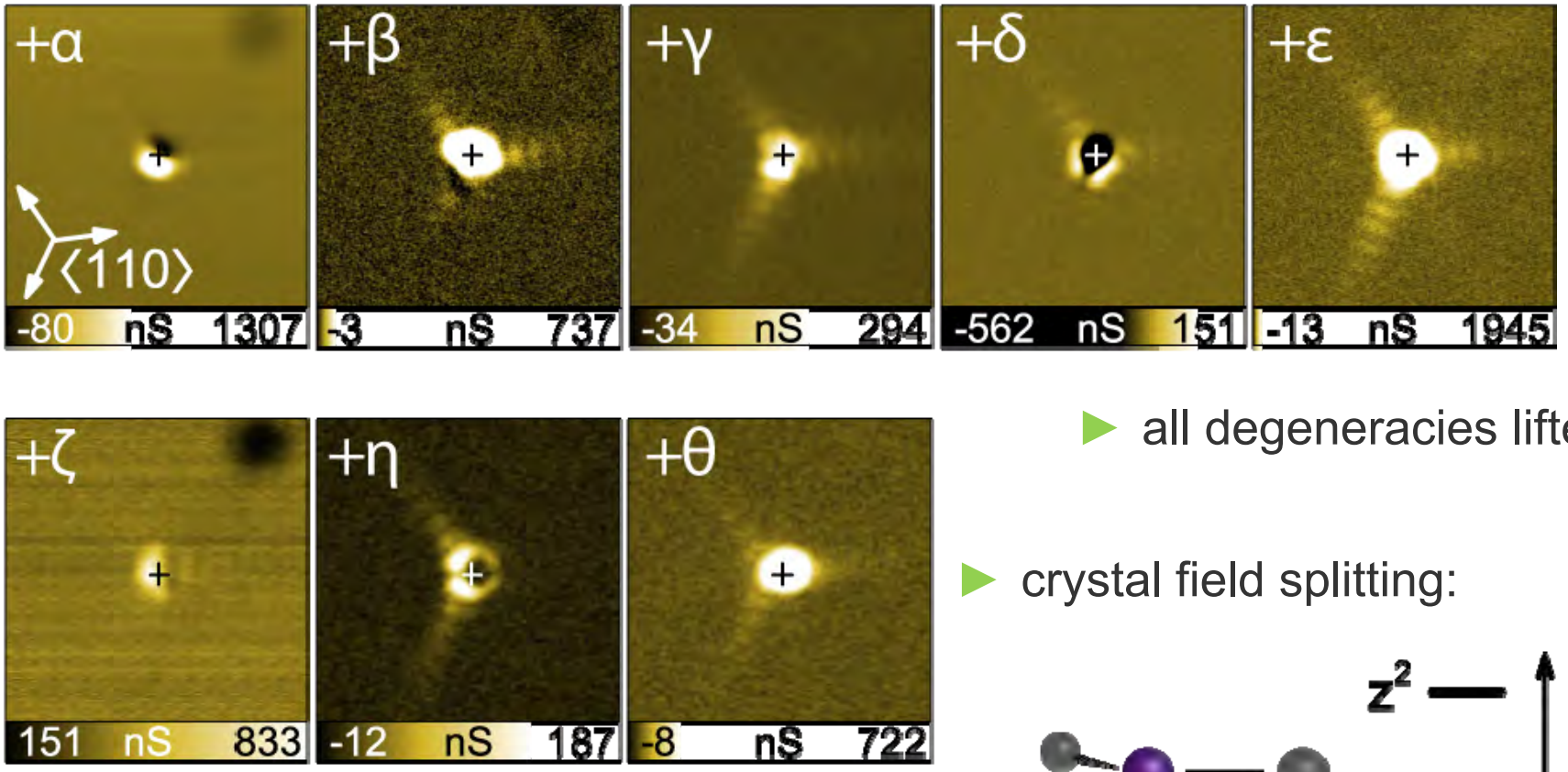
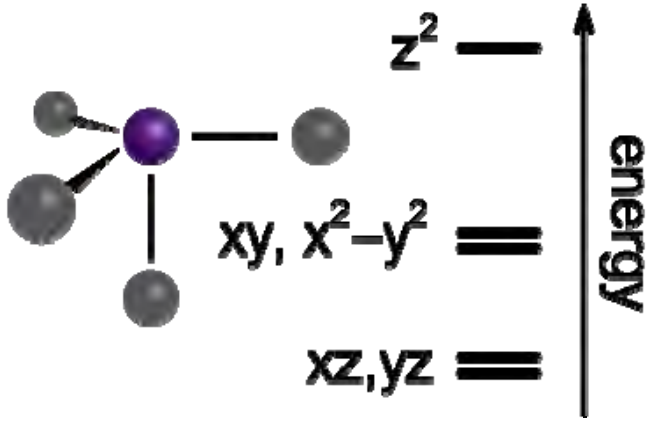


dI/dV maps, 8.8 x 8.8 nm^2

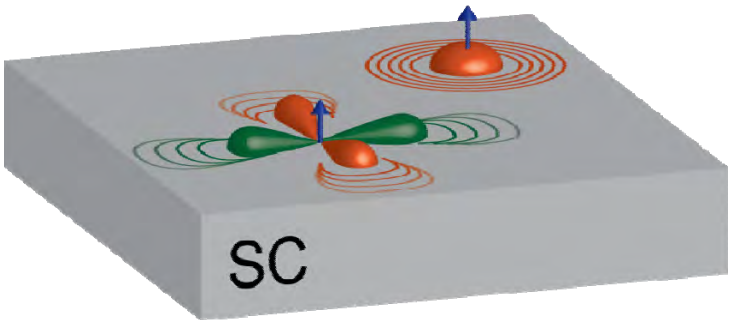
d_{xy,x^2-y^2} $d_{xz,yz}$ d_{z^2}

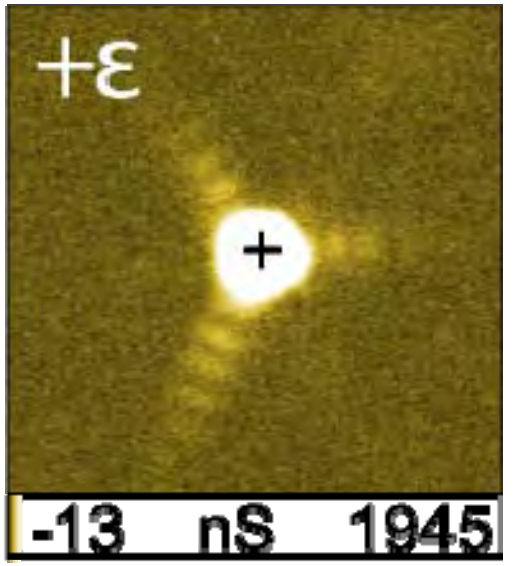
- all degeneracies lifted
- crystal field splitting:



M. Ruby et al., Phys. Rev. Lett. 117, 186801 (2016)

Shape and extension of Shiba states



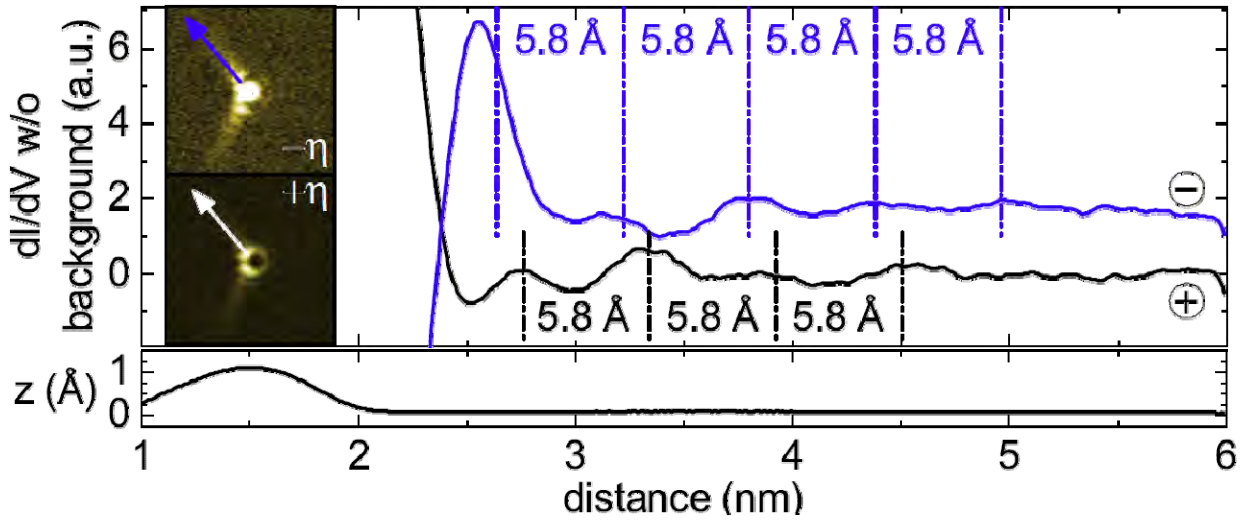


- maps reflect symmetry of singly occupied states
- extension?

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

$$\epsilon = \Delta \cos(\delta^{+} - \delta^{-})$$

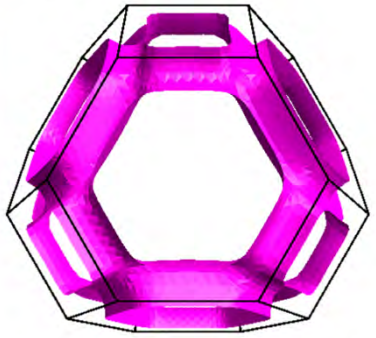
Shape and extension of Shiba states



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

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

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

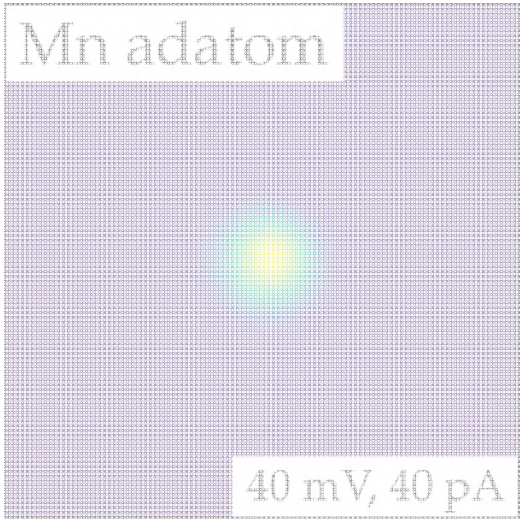


(p-d character)

$\langle 110 \rangle$ direction $\lambda_{\mathrm{F}} = 12.1 \pm 0.5$ Å

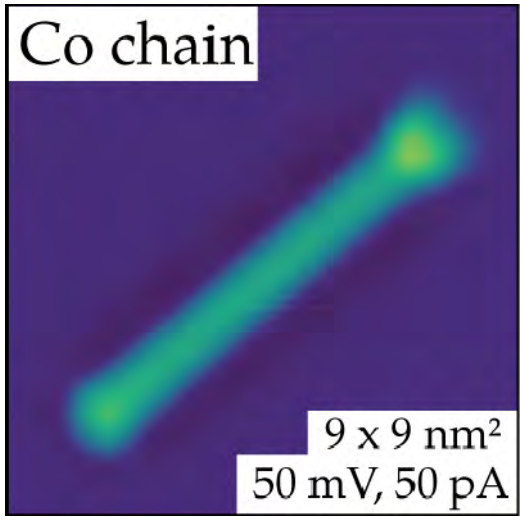
M. Ruby et al., Phys. Rev. Lett. 117, 186801 (2016)

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?

Toy model: Kitaev chain

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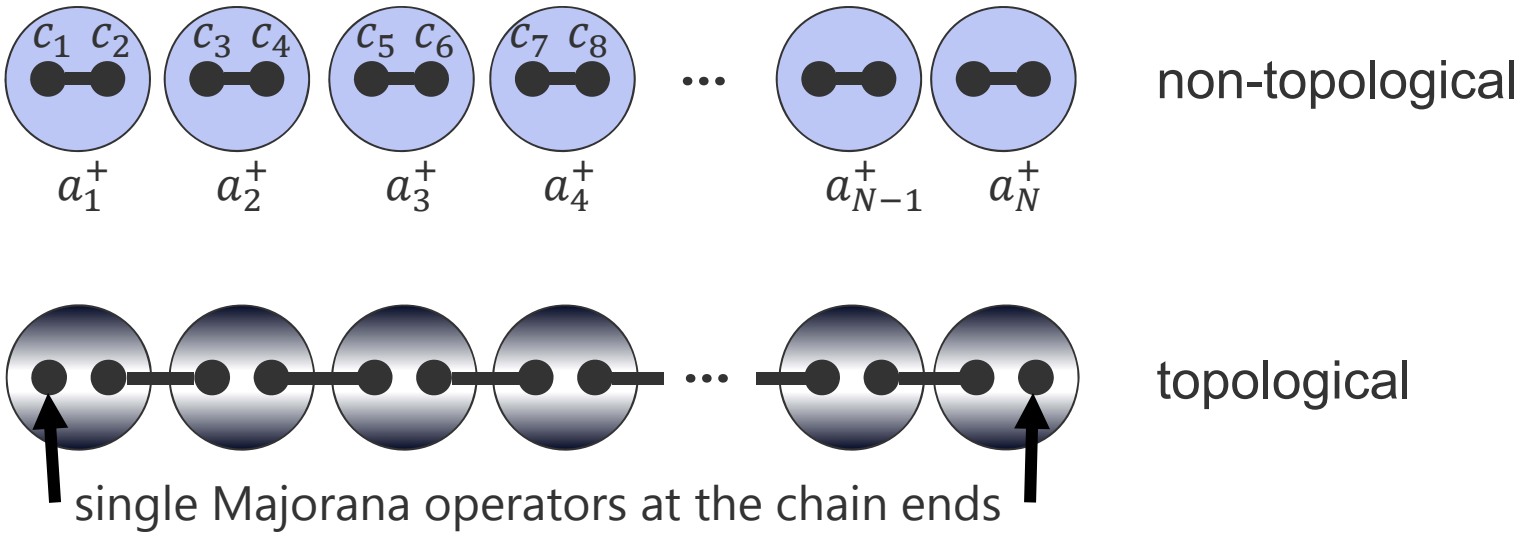
- 1D chain of atomic sites

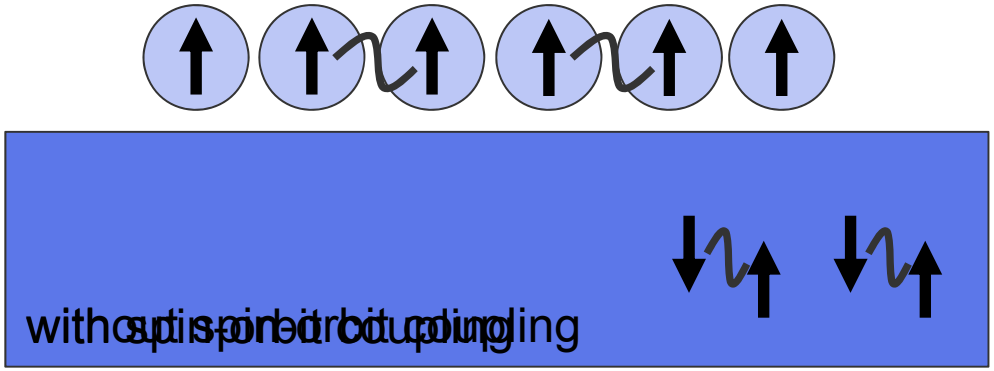


- conditions for the topological state:
  - spin-less bands along the chain
  - superconductivity within the chain

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

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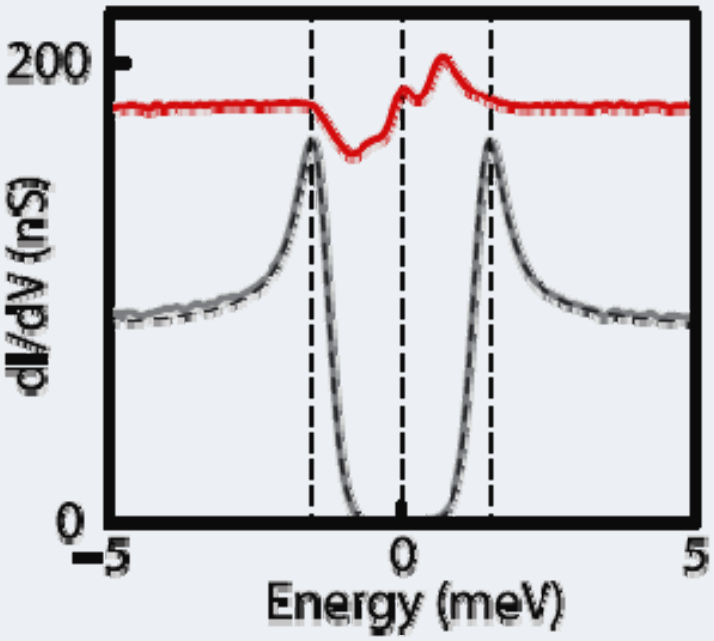
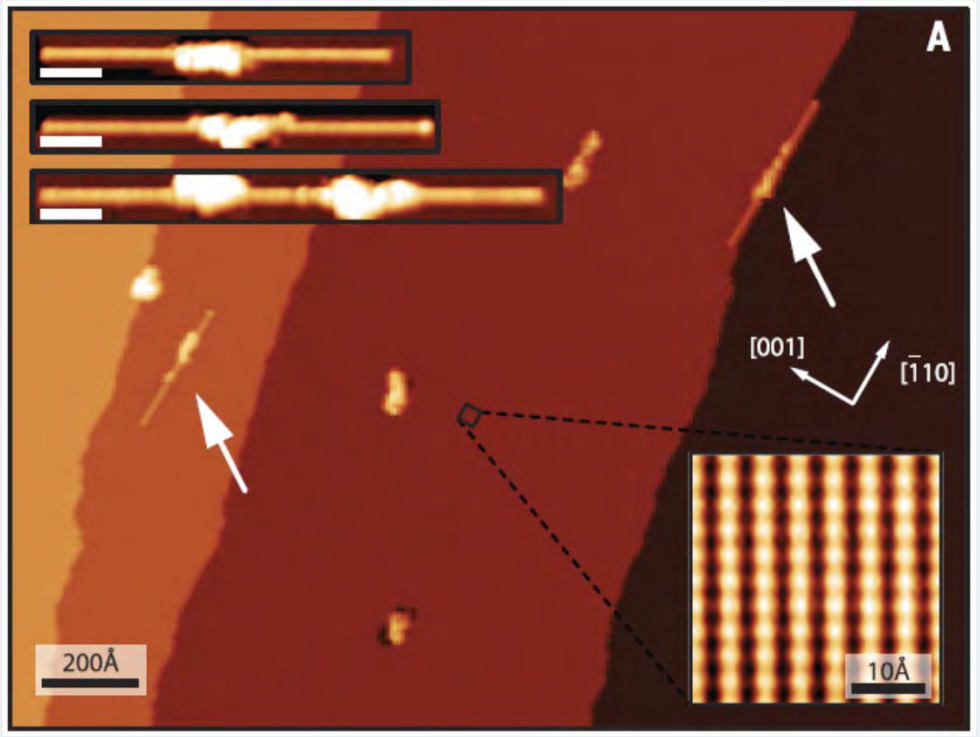
Nadj-Perge *et al.*, Science 346, 6209 (2014):



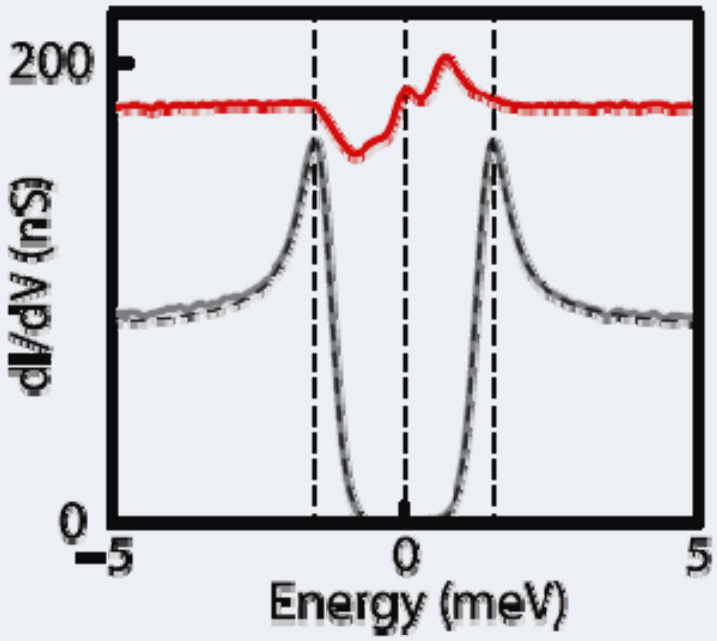


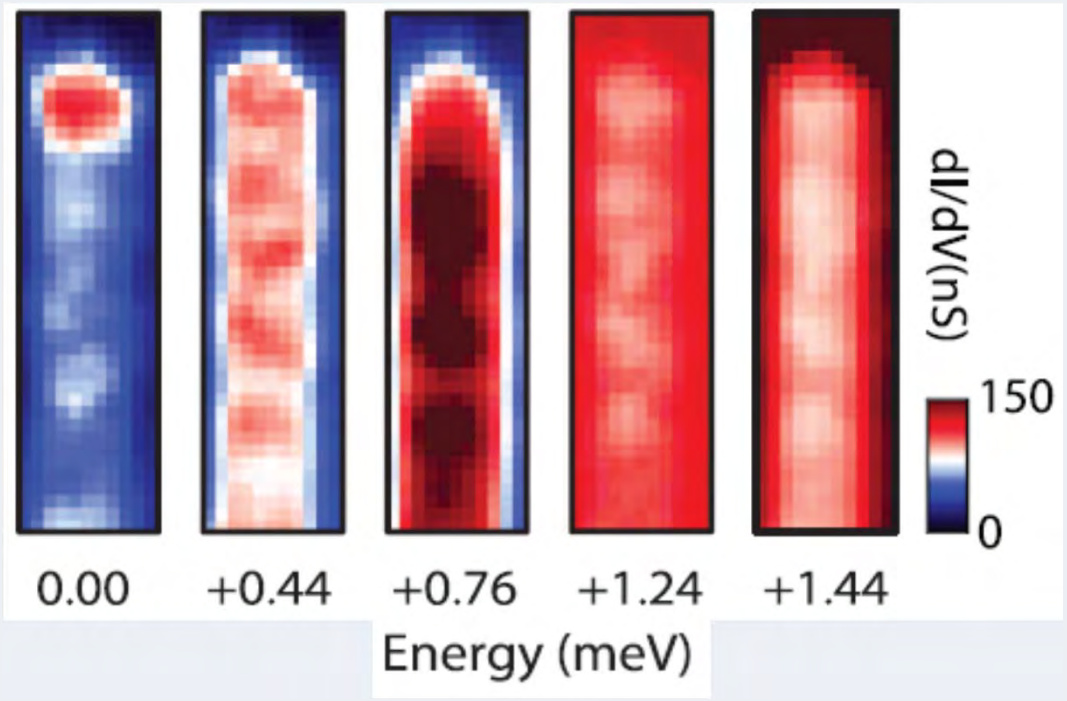
- Peak at zero bias
- Localized at chain end
- Interpretation as Majorana states
- Topological gap 200-300 μeV

Sub-gap structure in Fe chains

Freie Universität Berlin

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

Co chains on Pb(110): ferromagnetism

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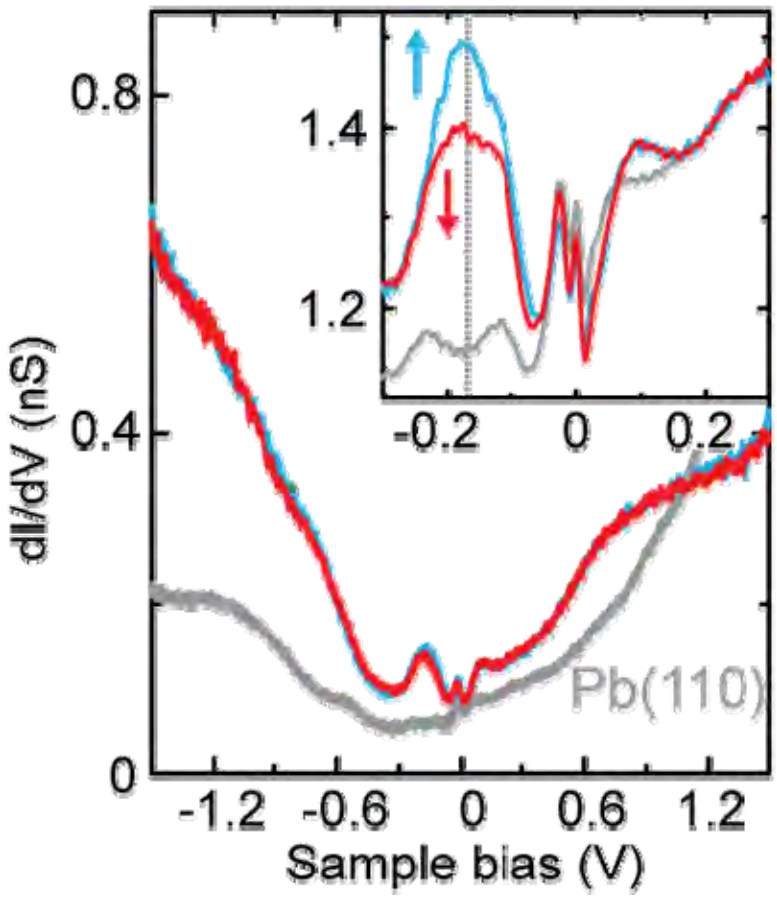
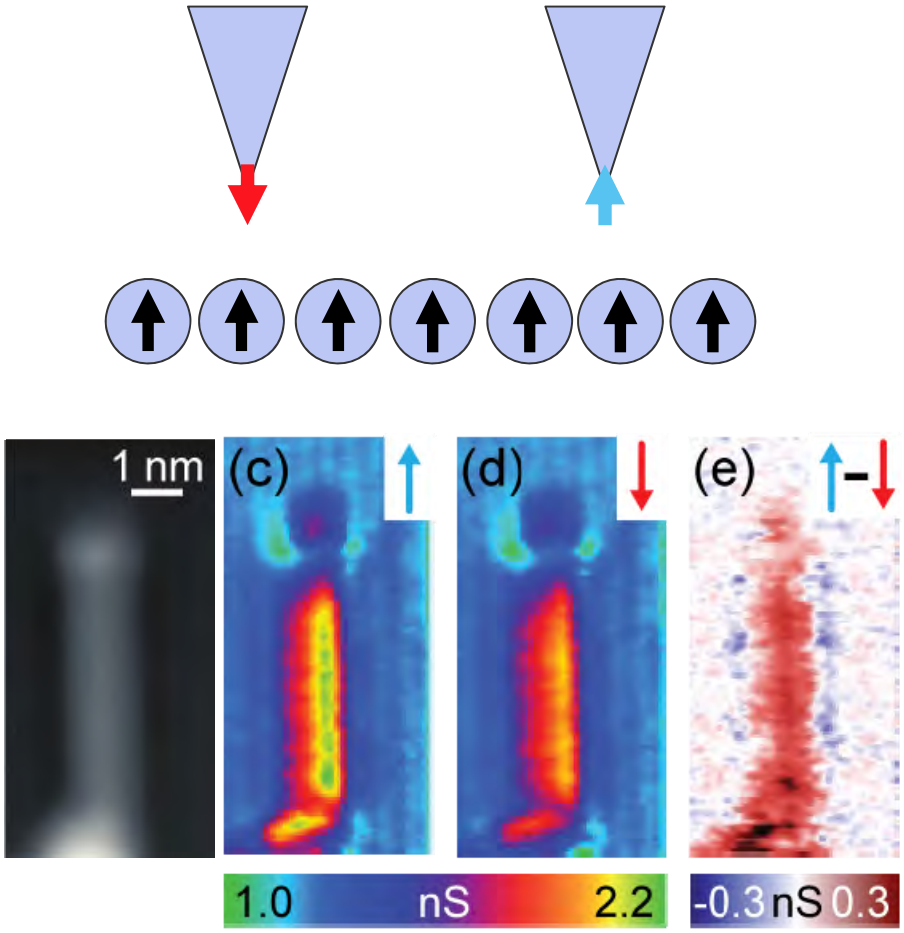
- check for ferromagnetism with spin-polarized tips





- spin-polarized d-bands
- ferromagnetic coupling

M. Ruby, et al., Nano Lett. 17, 4473 (2017)

Co chain on Pb(110): Shiba bands

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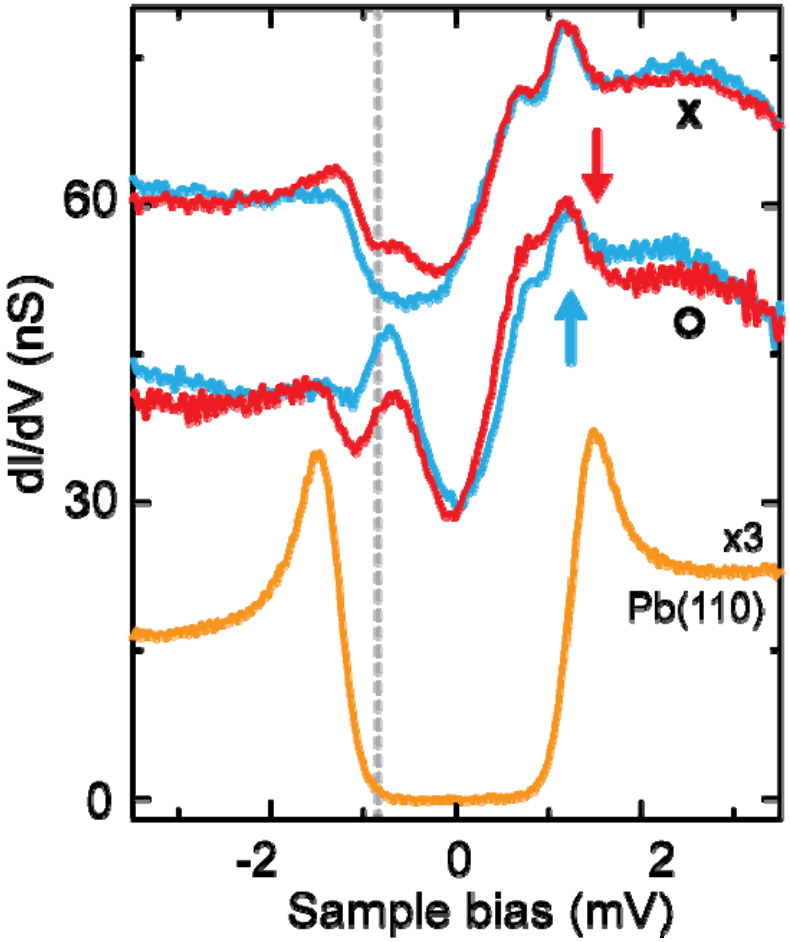
- check for Shiba bands with spin-polarized tips

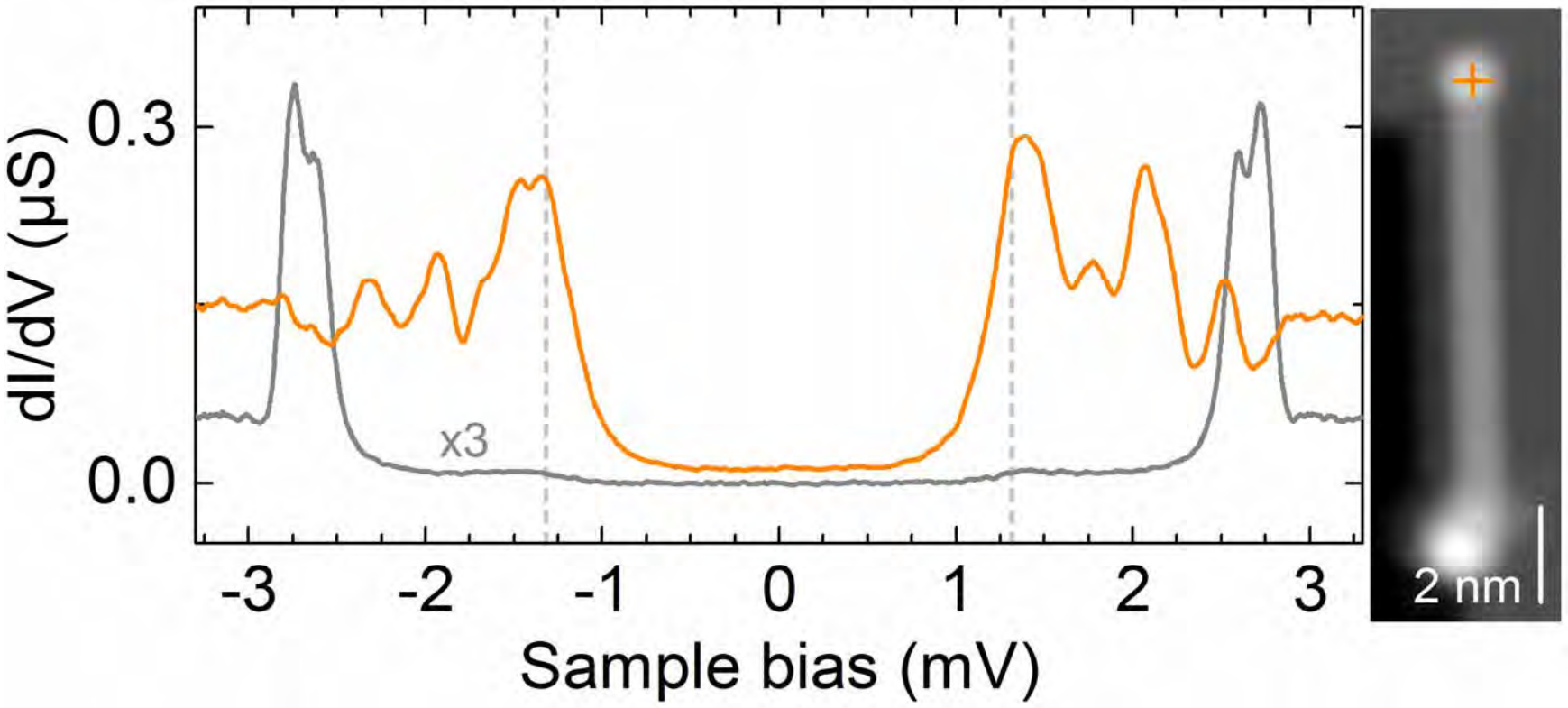


- spin-polarized Shiba-bands

M. Ruby, et al., Nano Lett. 17, 4473 (2017)

Co chains on Pb(110)

- check for superconductivity within the chain



- signatures for a topological gap observed?

M. Ruby, et al., Nano Lett. 17, 4473 (2017)

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

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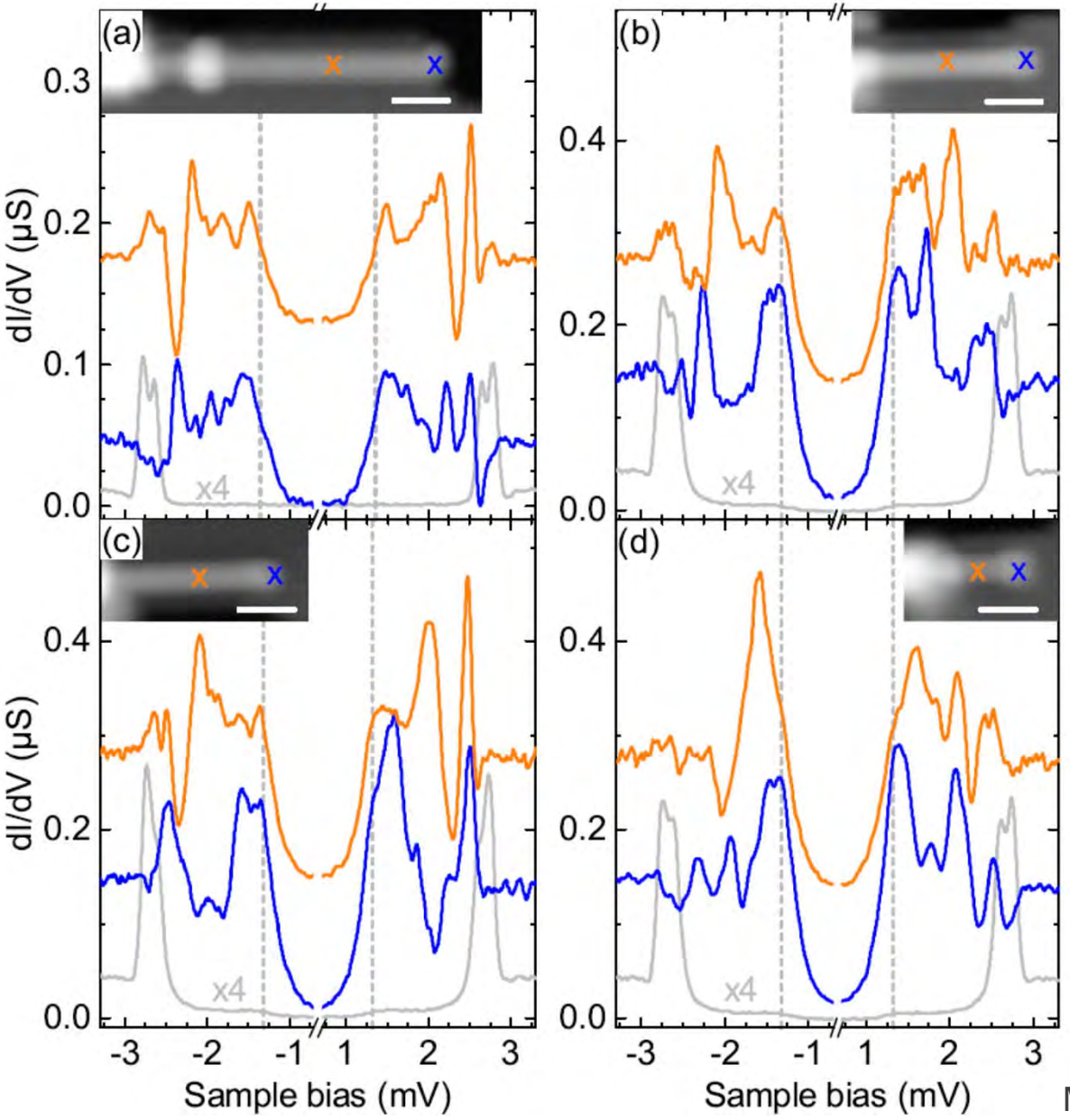

- peaks/shoulders close to zero energy
- chains look similar: 2.5-9.4 nm length

M. Ruby, et al., Nano Lett. 17, 4473 (2017)

Co chains on Pb(110): localization of states

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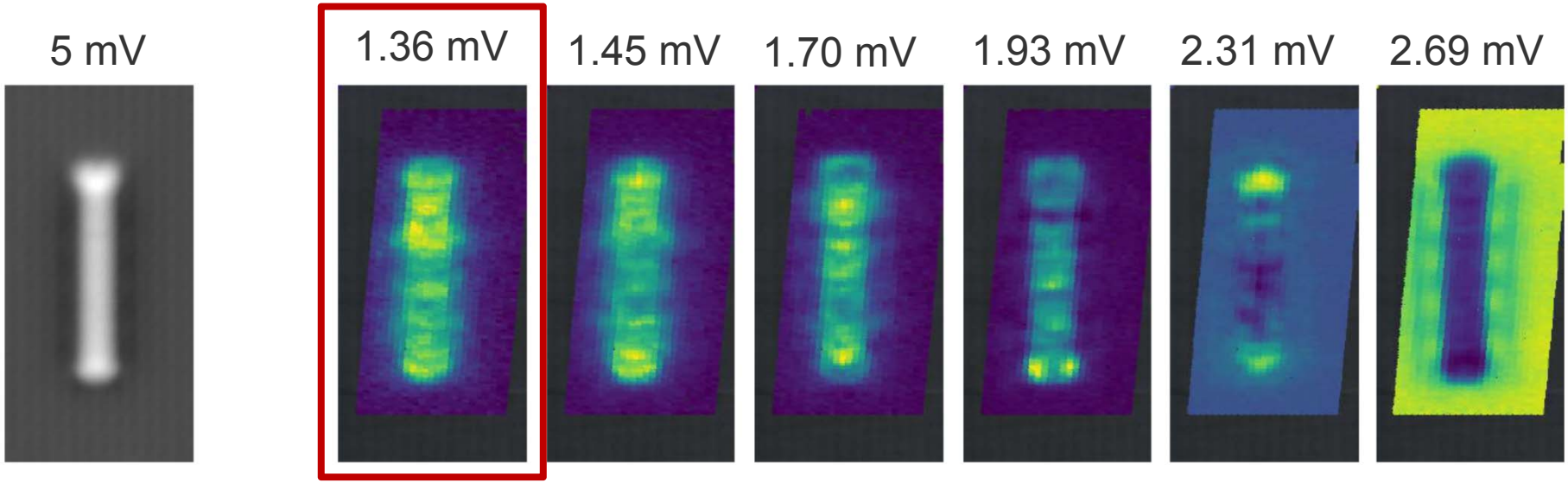
- Conductance maps



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

M. Ruby, et al., Nano Lett. 17, 4473 (2017)

Band structure of Co chains

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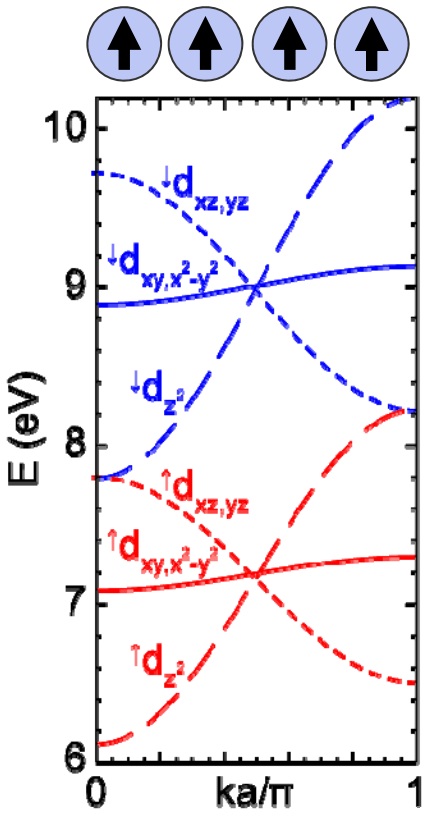
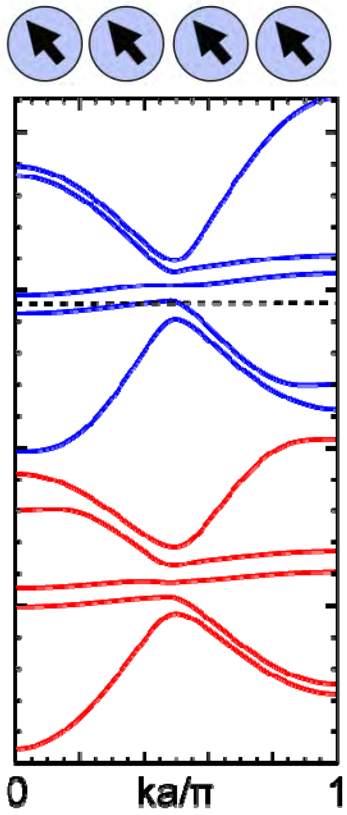
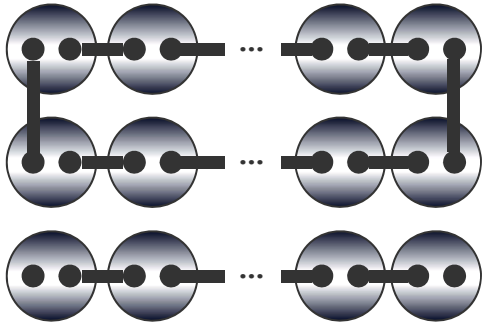
without spin-orbit coupling



with spin-orbit coupling



- # crossings at E_F:



→ odd number required

- Fe could have *odd* number of Fermi points
- Co could have *even* number of Fermi points

Conclusions

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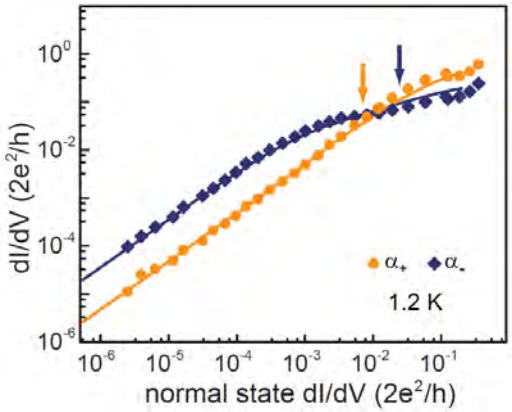
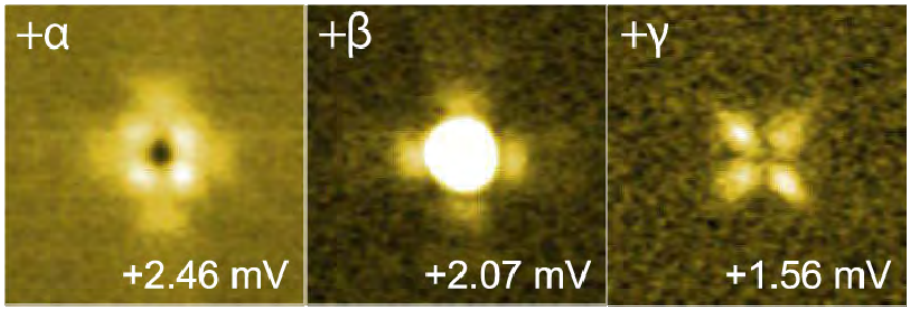
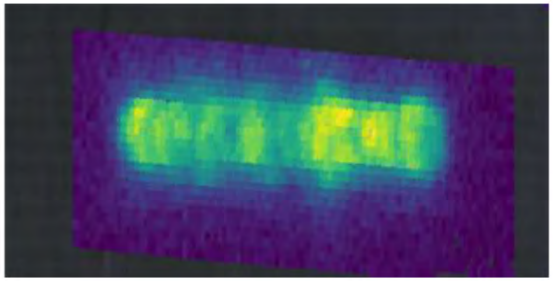
- Two transport mechanisms through Shiba states:
  - Single electron tunneling
  - Resonant Andreev reflections
  - Thermal relaxation from Shiba states



- 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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Yang Peng, Falko Pientka, Felix von Oppen