Two-dimensional Shiba lattices as a possible platform for crystalline topological superconductivity

Martina O. Soldini ®[1]✉, Felix Küster[2]✉, Glenn Wagner[1], Souvik Das[2], Amal Aldarawsheh ®[3,4], Ronny Thomale ®[5,6], Samir Lounis ®[3,4], Stuart S. P. Parkin ®[2], Paolo Sessi[2] & Titus Neupert ®[1]

Journal Club, 27.02.2026,

Andrea Chieppa

Scanning Tunnelling Microscopy

metal   barrier   metal

$$R_{A \to B} = \frac{2\pi}{\hbar} \sum_{k,k',\sigma} |T_{kk'}|^2 \{ f(E_A)(1 - f(E_B)) - f(E_B)(1 - f(E_A)) \} \delta(E_B + eV - E_A)$$
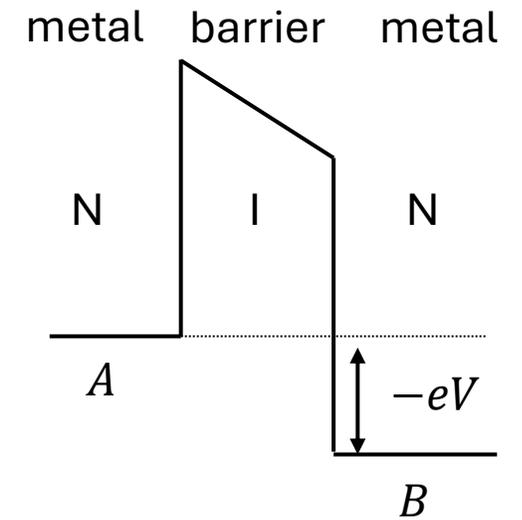
$$R_{A \to B} = \frac{2\pi}{\hbar} \sum_{\sigma} \int d\epsilon \, d\epsilon' D_A(\epsilon) D_B(\epsilon') \, |T(\epsilon, \epsilon')|^2 \{ f(\epsilon)(1 - f(\epsilon')) - f(\epsilon')(1 - f(\epsilon)) \} \delta(\epsilon' - \epsilon + eV)$$

$$R_{A \to B} \propto I \propto \int d\epsilon' D_B(\epsilon') \{ f(\epsilon' + eV) - f(\epsilon') \}$$

With an STM you can:

1. Measure the density of states locally (LDOS)

2. Fix the current, measure topography $I \propto e^{-x/l}$

In the following, $T = 500 \text{ mK} \leftrightarrow 50 \text{ μV}$

Musée d'histoire des sciences, Genève, CH
Scanning tunneling microscope - Wikipedia

Magnetism and Superconductivity

Phys. Rev. Lett. **1**, 92, 1958

SPIN EXCHANGE IN SUPERCONDUCTORS

B. T. Matthias, H. Suhl, and E. Corenzwit

Bell Telephone Laboratories,
Murray Hill, New Jersey
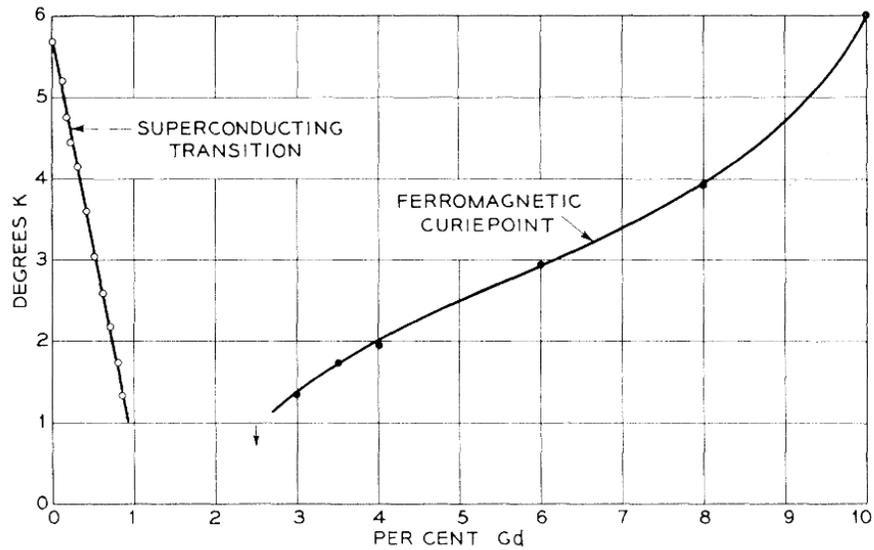(Received July 15, 1958)

FIG. 3. Ferromagnetic and superconducting transition temperatures of solid solutions of gadolinium in lanthanum.
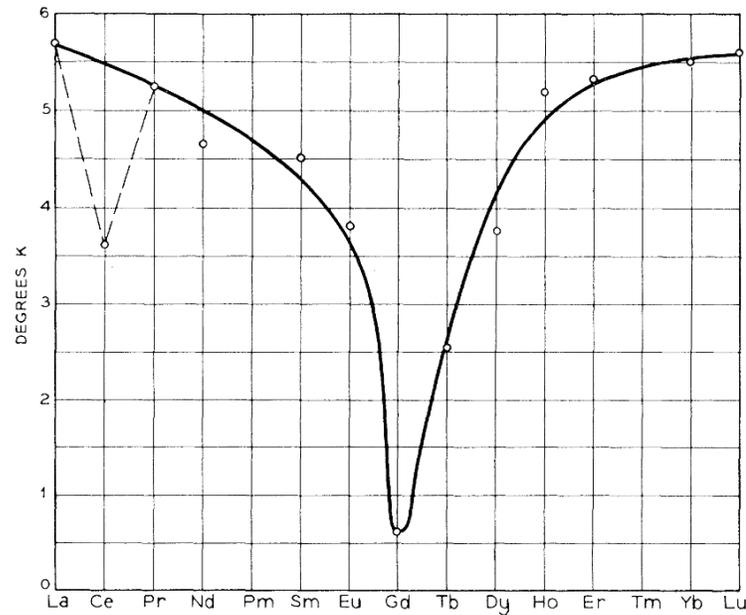
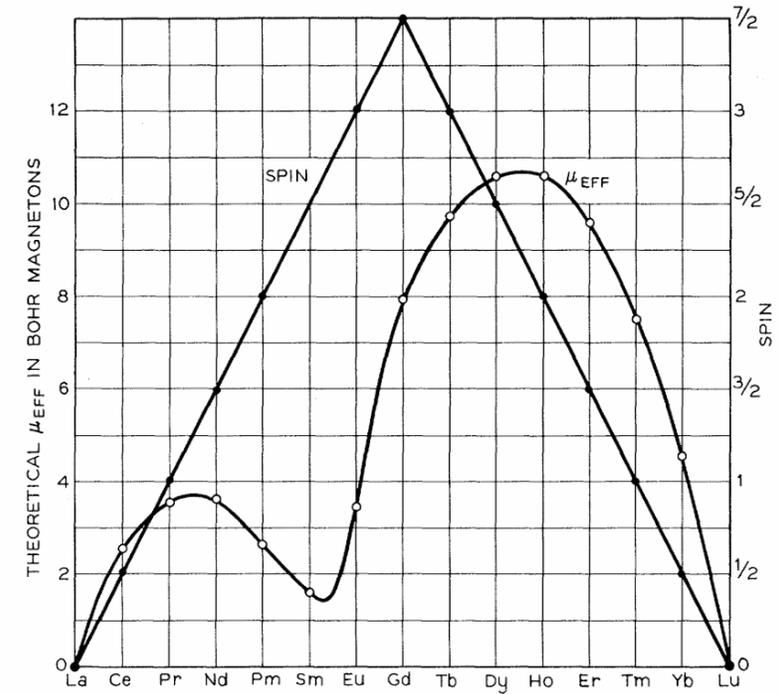FIG. 2. Superconducting transition temperatures of 1 at.% rare earth solid solutions in lanthanum.

FIG. 1. Effective magnetic moments and spins of the rare earth elements (see reference 2).

also: J. H. van Vleck - Nobel Lecture

Matthias rules

From Wikipedia, the free encyclopedia

conventional

In physics, the **Matthias rules** refers to a historical set of empirical guidelines on how to find superconductors.

1. High symmetry is good, cubic symmetry is the best.
2. High density of electronic states is good.
3. Stay away from oxygen.
4. Stay away from magnetism
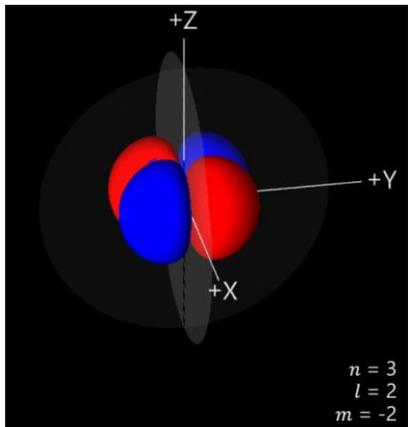5. Stay away from insulators.
6. Stay away from theorists!

Structure of the Journal Club

- Single atom of Cr on Nb

Yu-Shiba-Rusinov states •

- Lattices of Cr atoms on Nb

Yu-Shiba-Rusinov bands •

- Theory work

Crystalline Topological Superconductivity •

The isolated chromium atom

d_{xy}

n = 3
l = 2
m = -2

d_{yz}

n = 3
l = 2
m = -1

d_{z^2}

n = 3
l = 2
m = 0

d_{xz}

n = 3
l = 2
m = 1
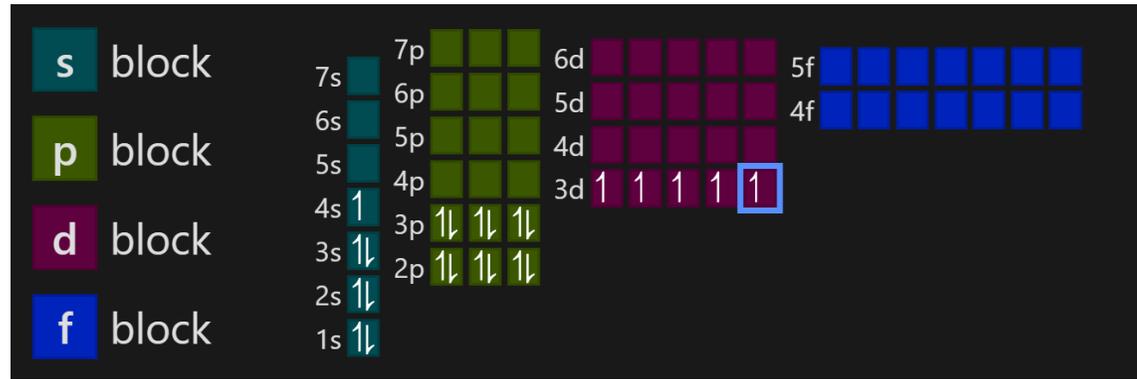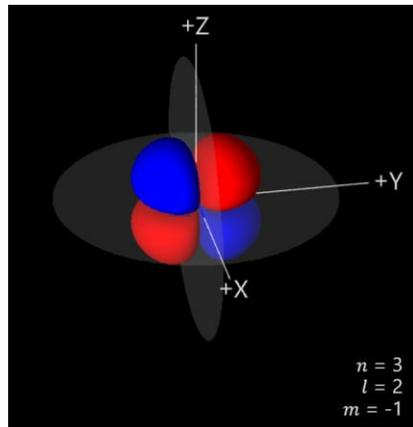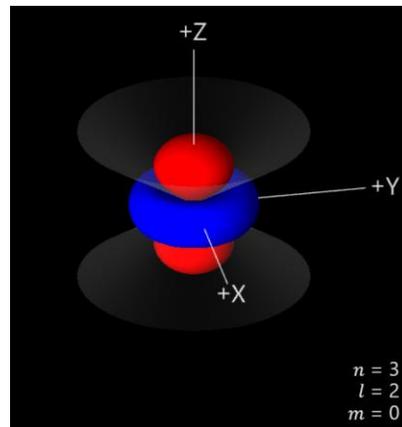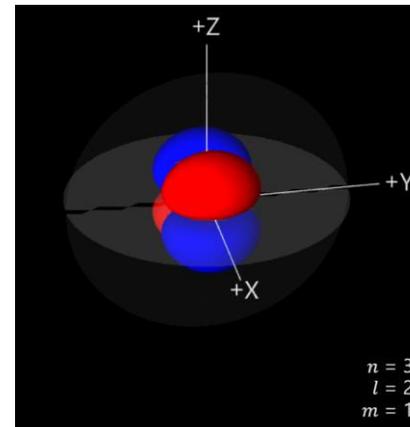
$d_{x^2-y^2}$

n = 3
l = 2
m = 2
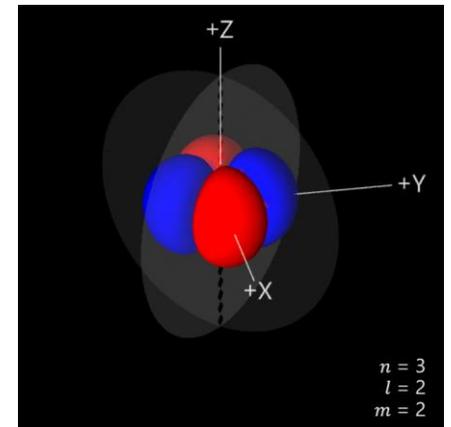
Surface preparation and Cr deposition

Topographic contrast (constant current)
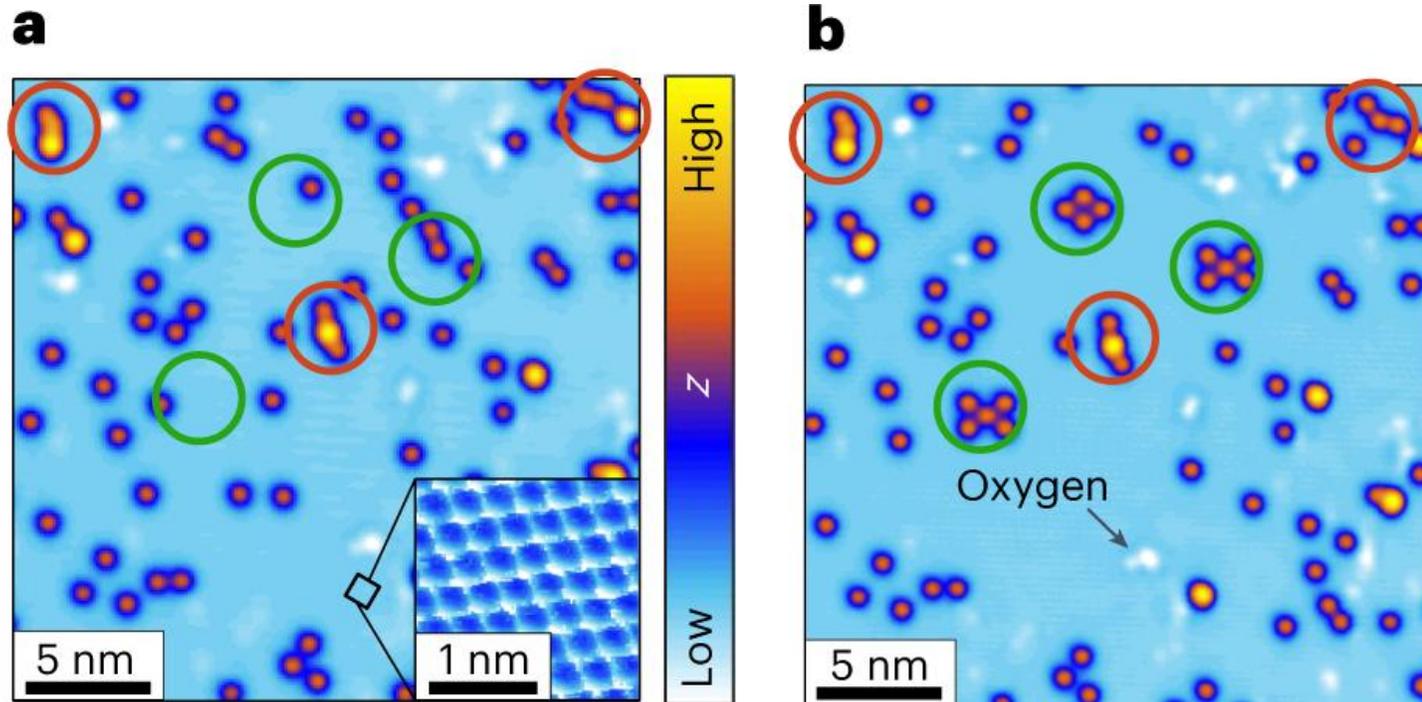
- Cr atoms (bright spots) on Nb(110) (blue surface)
- Preparation of the surface: > 2000 ℃ [1]
- Atomic manipulation: constant current 70 nA, $V_s = -5\ \mathrm{mV}$,

[1] Odobesko, A. et al., Preparation and electronic properties of clean superconducting Nb(110) surfaces, Phys. Rev. B 99, 115437, DOI

Single Cr atom on Nb (110)

$I = 500 \text{ pA};$ $V_{\text{sample}} = -5 \text{ mV};$ $\delta V = 50 \text{ }\mu\text{V}$
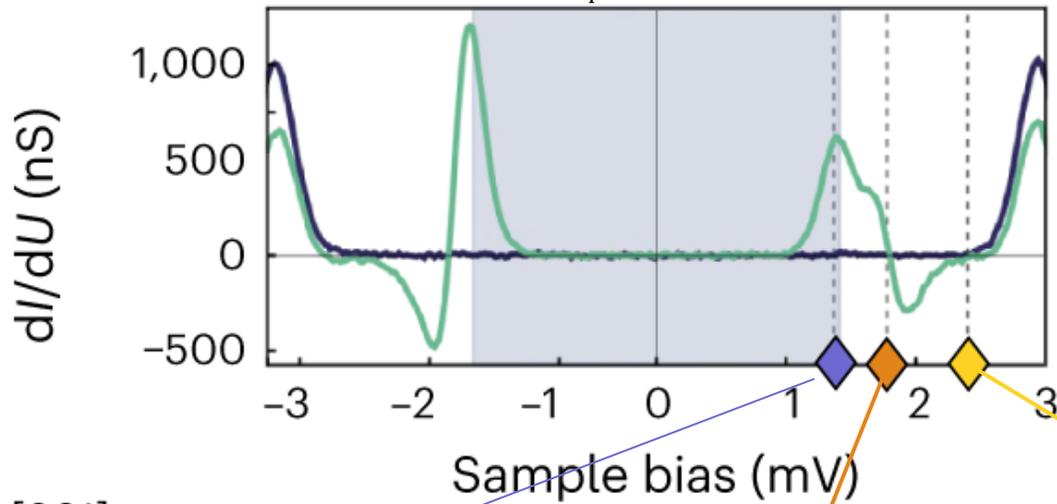
— Spectra on Cr atom
— Spectra on Nb surface

Spatial character can be obtained by fixing the sample bias and scanning the region nearby the magnetic atom
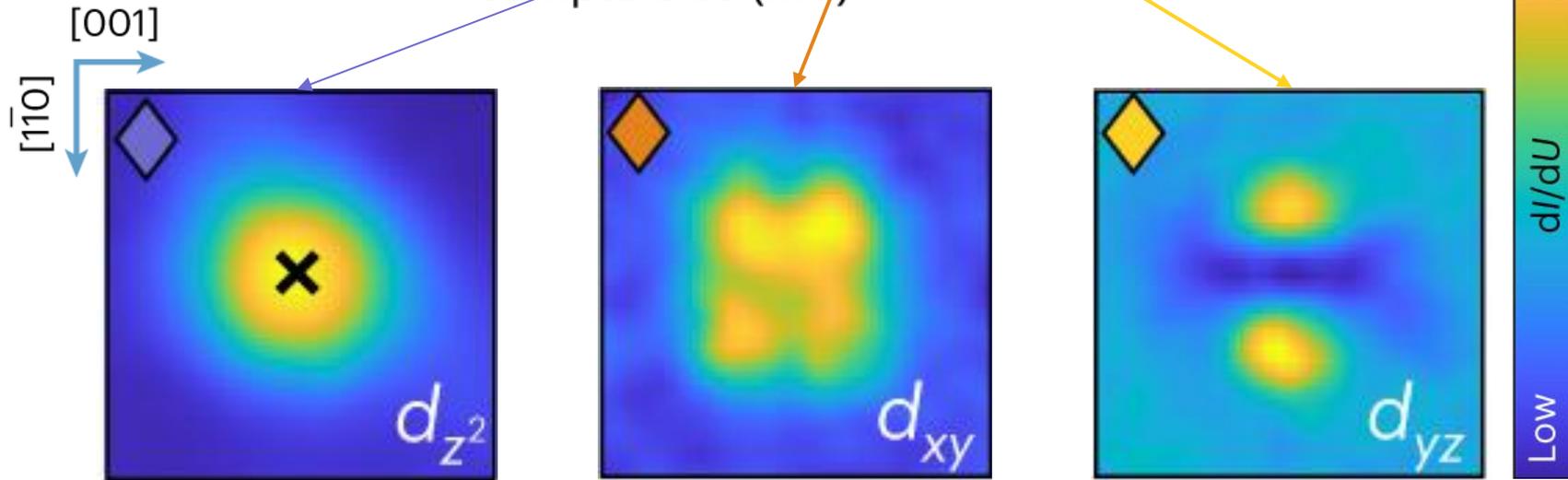
*no scale reported

Crystal lattices explored

	a	b	c	d	e
Termination along	[001] [1$\bar{1}$0]	[1$\bar{1}\bar{1}$] [1$\bar{1}$1]	Double step [2$\bar{2}$1] [2$\bar{2}\bar{1}$]	[1$\bar{1}\bar{1}$] [1$\bar{1}$1]	[001] [1$\bar{1}$0]

Two lattices created with Cr atoms

Spin resolved STM in constant height mode, B = 0.7 T

$a\,[001] = 0.66$ nm
$b\,[1\bar{1}0] = 0.93$ nm

$a\,[1\bar{1}\bar{1}] = 0.85$ nm
$b\,[1\bar{1}1] = 0.85$ nm

- Spin polarized STM

- Alternating spin contrast

- Antiferromagnetic ground state

$I = 500$ pA; $V_{\text{sample}} = -3$ mV; $V_{\text{tip}} = 0.33$ mV; $\delta V = 80$ μV

Crystal lattices explored
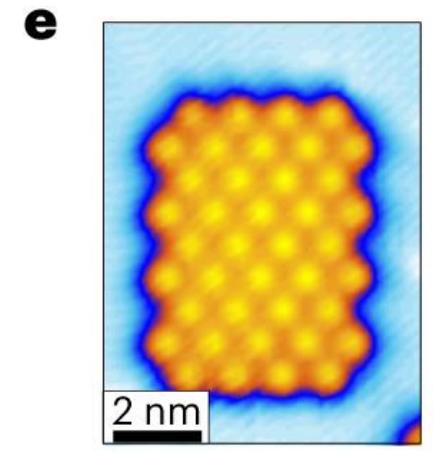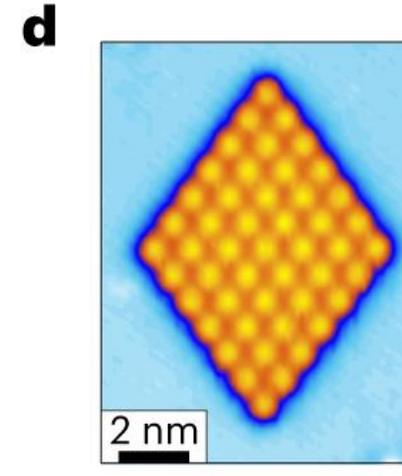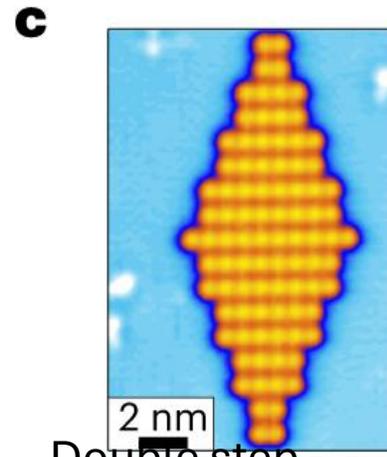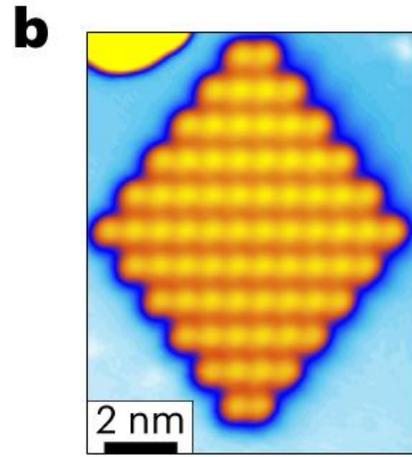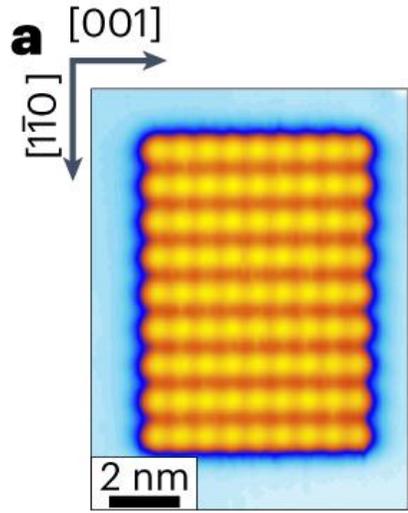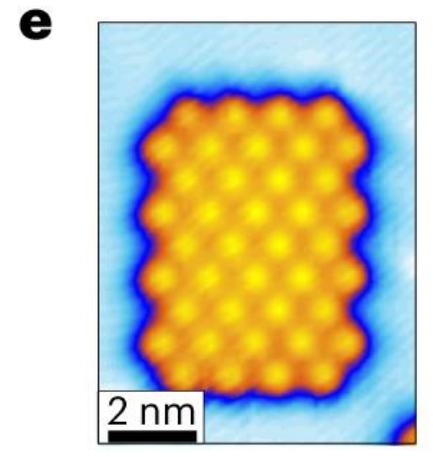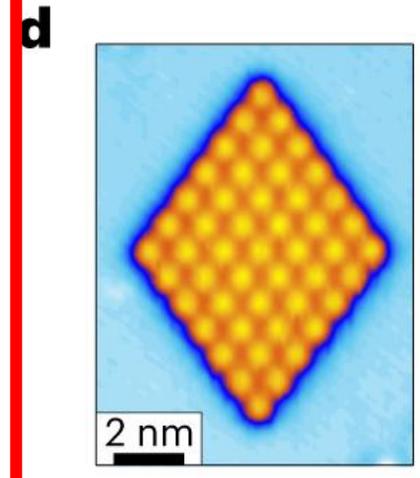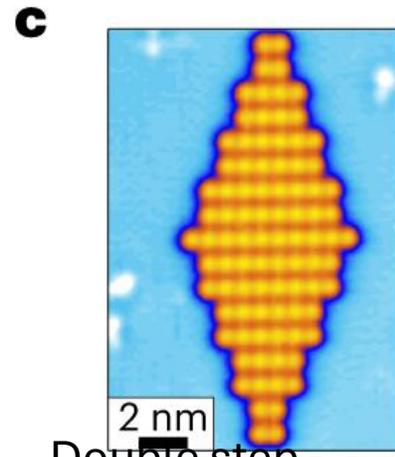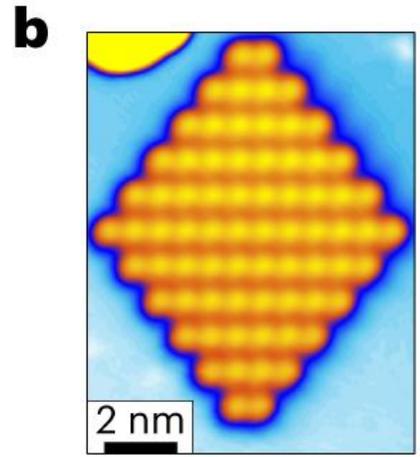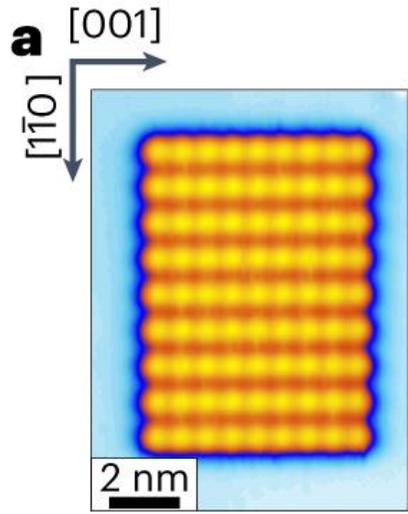
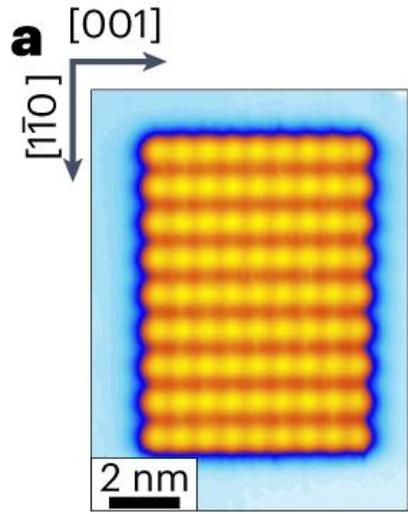|	**a** [001] [1̄0]	**b**	**c** Double step	**d**	**e**
Termination along	[001] [11̄0]	[11̄1̄] [11̄1]	[22̄1] [22̄1̄]	[11̄1̄] [11̄1]	[001] [11̄0]
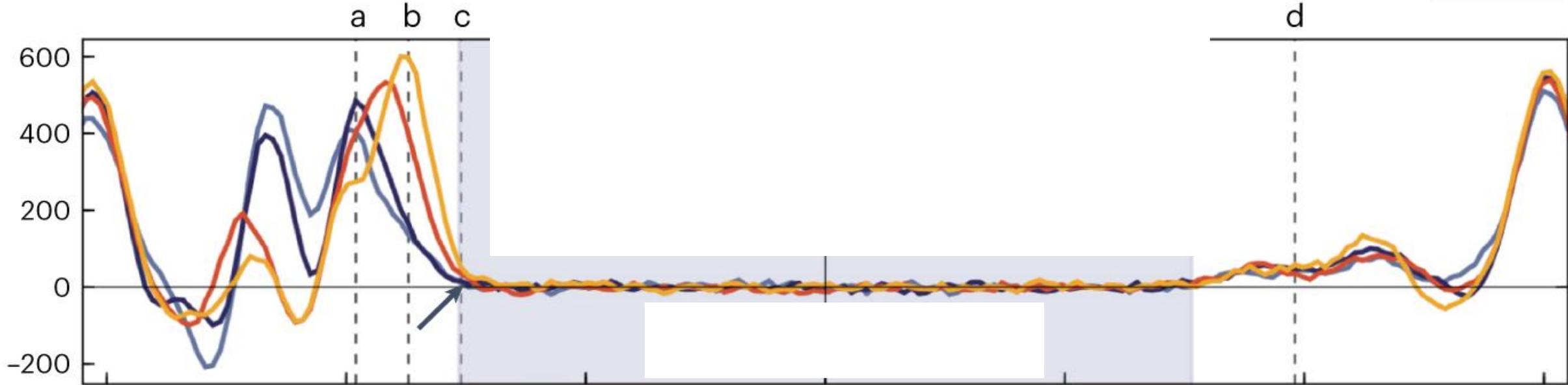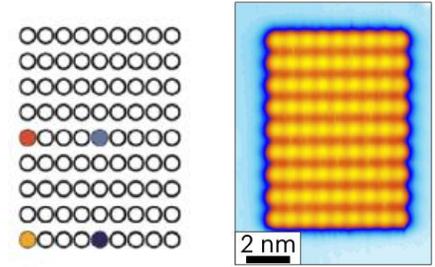
Corners, Edges, Bulk: rectangular lattice

- Position dependent spectrum
- Toward edge stronger spectral intensity at low energies with respect to the bulk
- Asymmetric around E_F: particle-hole asymmetric

Corners, Edges, Bulk: rectangular lattice
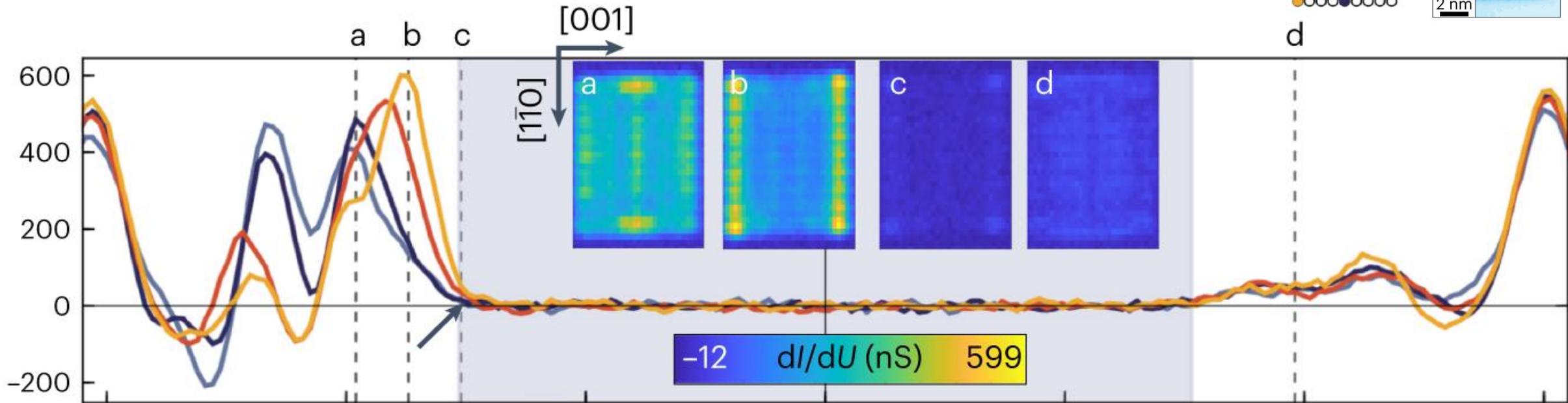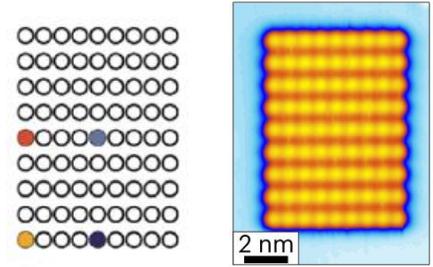
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Corners, Edges, Bulk: rectangular lattice
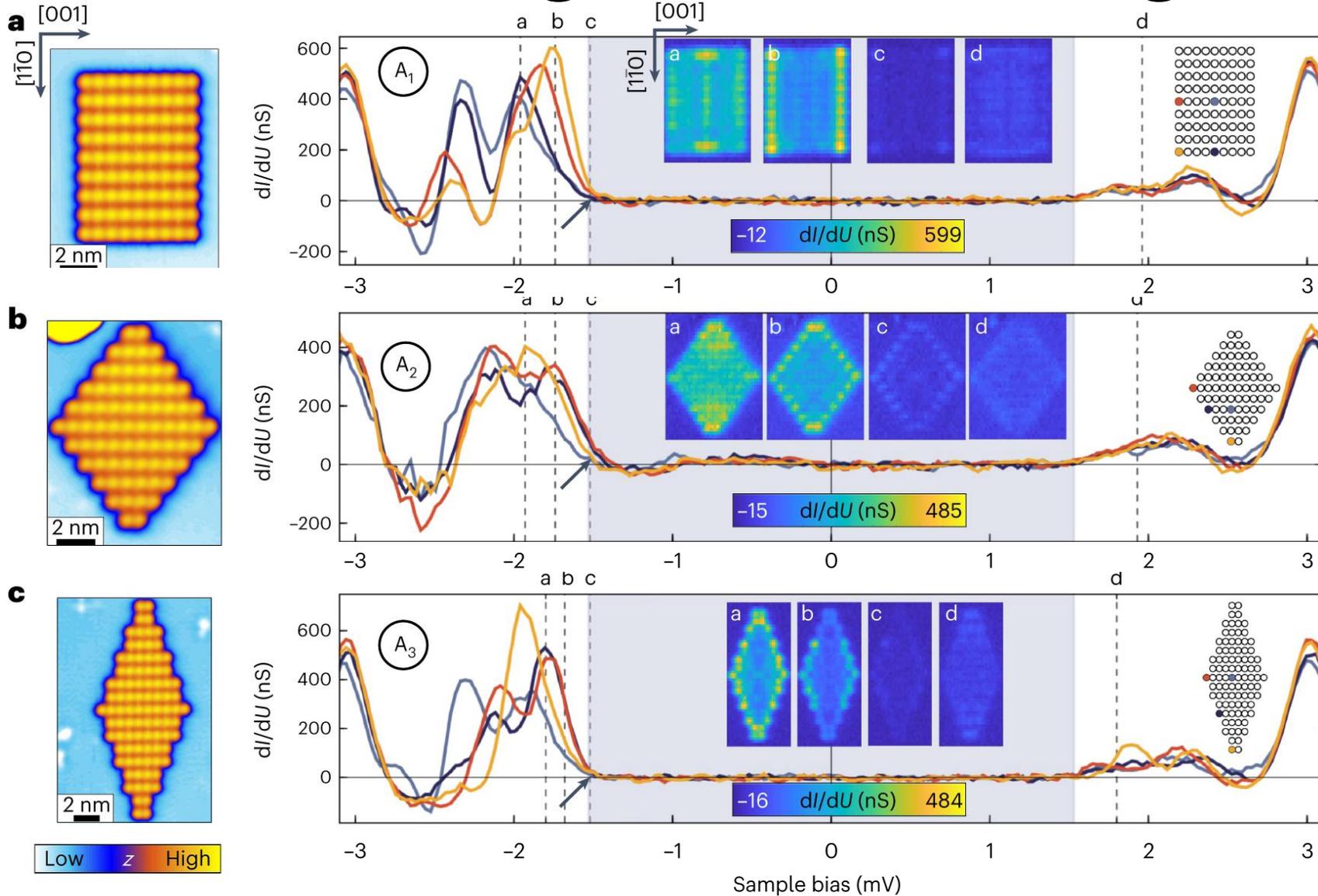
- Bulk properties termination independent

- Edge modes are termination dependent

- Gapped spectrum

Crystal lattices explored

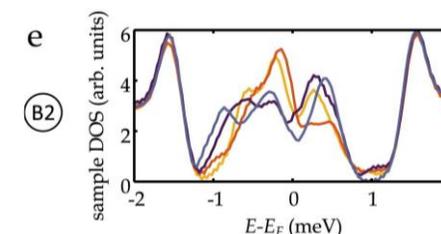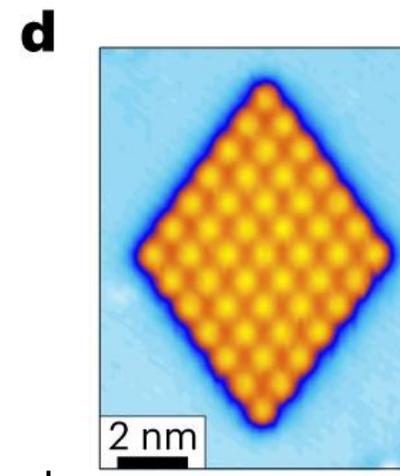| Termination along | [001] [1$\bar{1}$0] | [1$\bar{1}\bar{1}$] [1$\bar{1}$1] | Double step [2$\bar{2}$1] [2$\bar{2}\bar{1}$] | [1$\bar{1}\bar{1}$] [1$\bar{1}$1] | [001] [1$\bar{1}$0] |
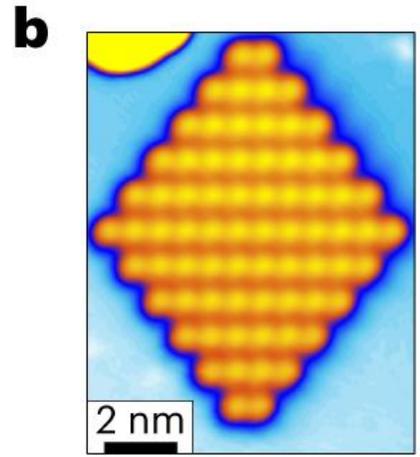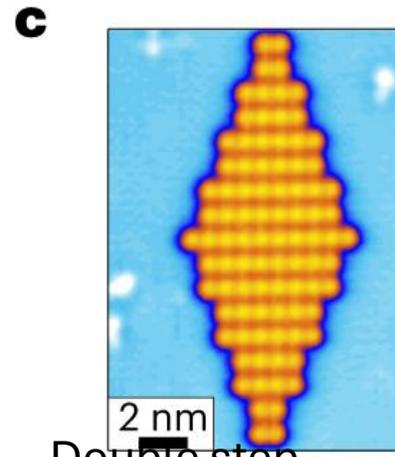
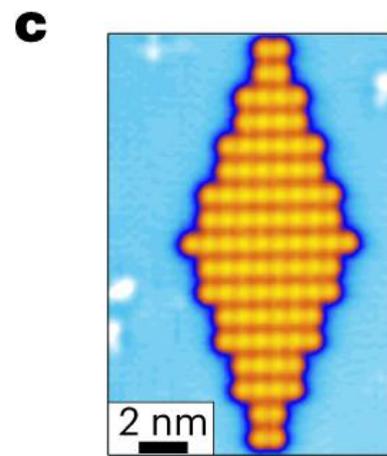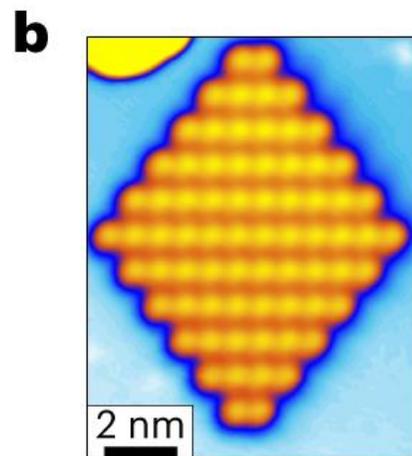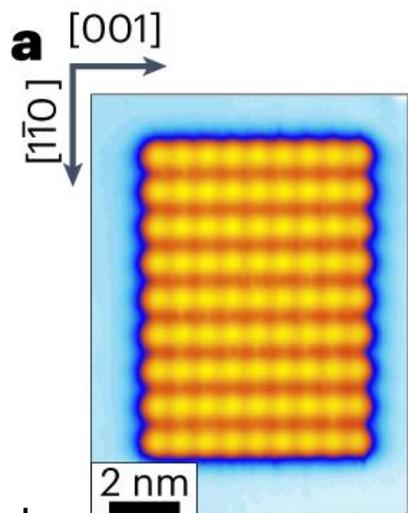# Corners, Edges, Bulk: rhombic lattice
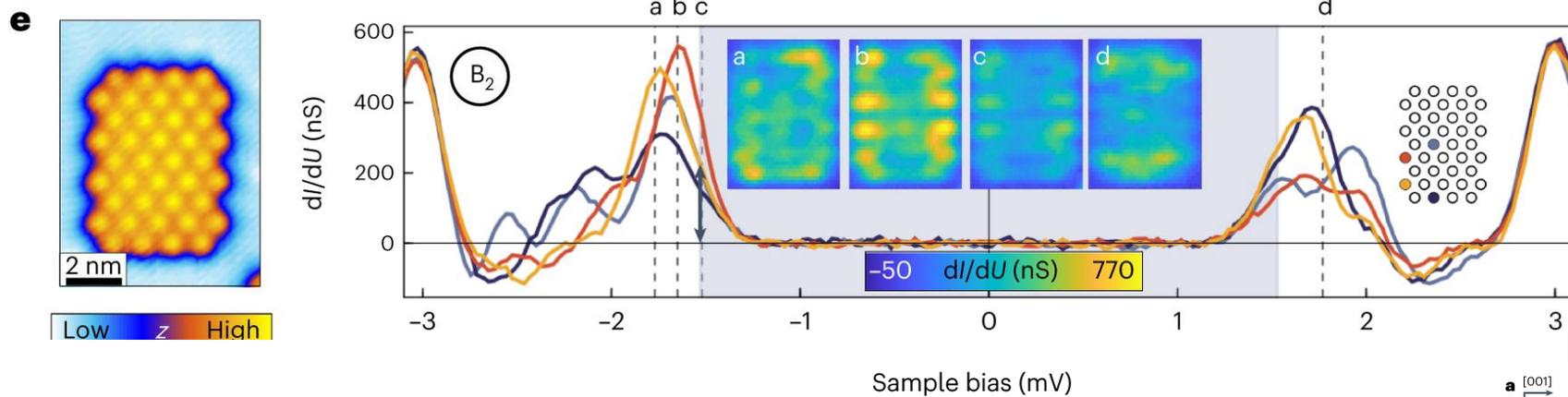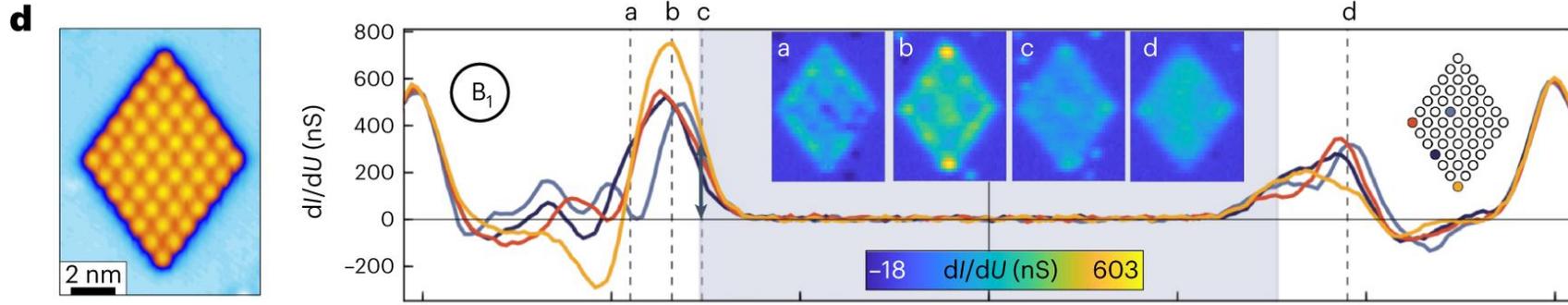
- Gapless spectrum

For reference, the rectangular lattice
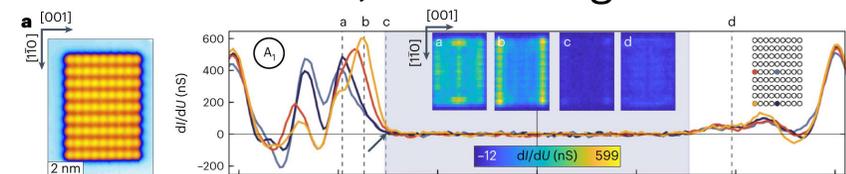
Lattice effect on the bulk properties
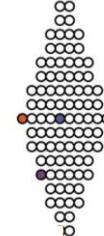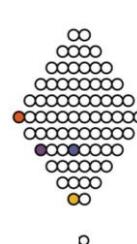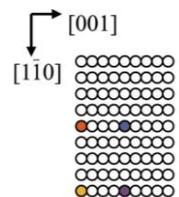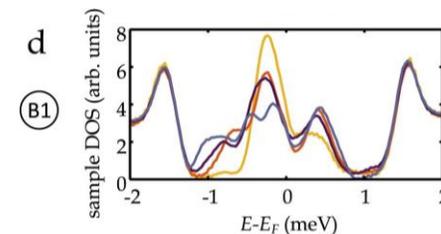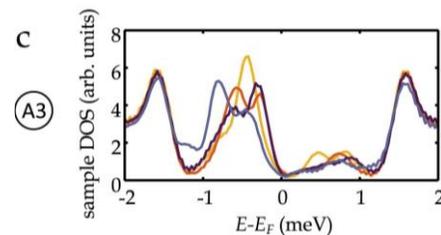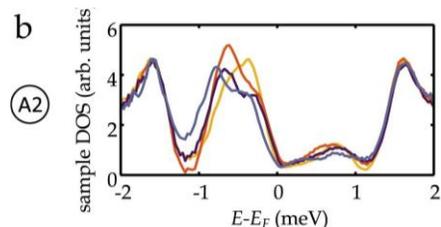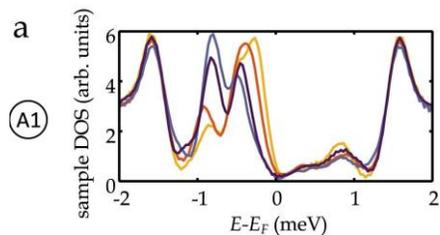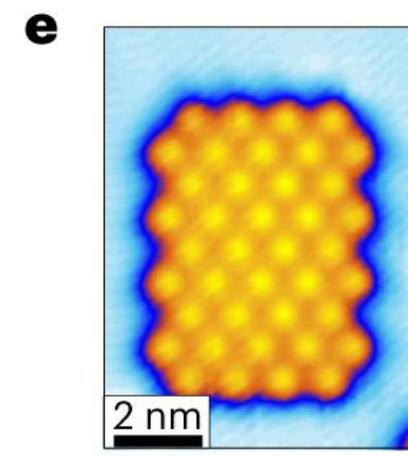
Theory

- Single orbital tight binding models (d_{z^2})
- Nearest-neighbour
- Next nearest-neighbour
- Rashba spin orbit coupling
- s-wave superconductivity of the substrate
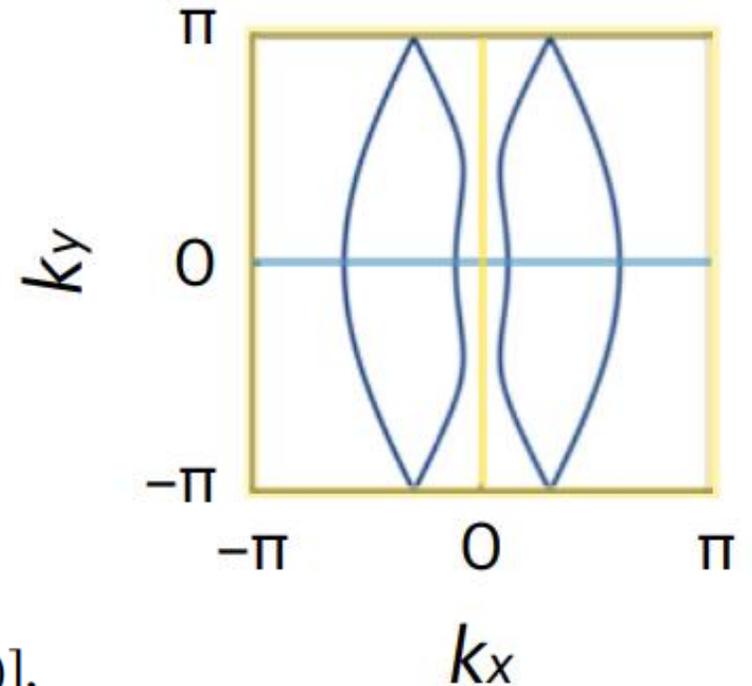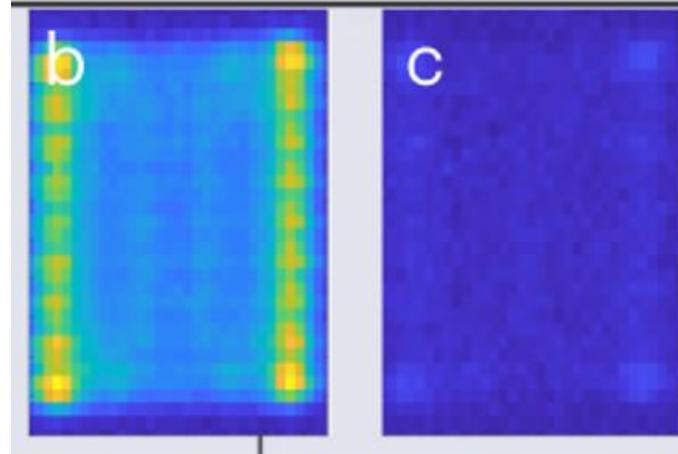- antiferromagnetic ordering of the magnetic moments of the Cr adatom
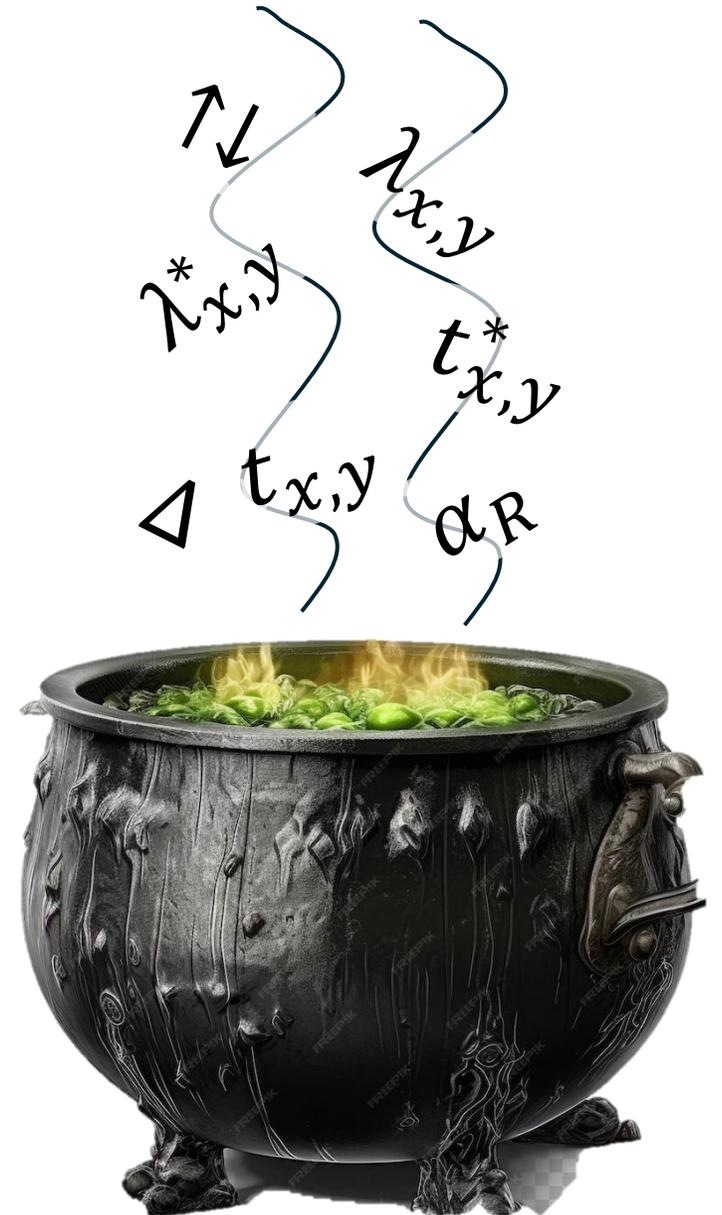
Symmetries

- Symmetries: $(M_x, M_y)\mathcal{T}, \mathcal{C}$ $(C_2 = M_x M_y)$
- Four paths are left invariant under action of the symmetries $(\text{BDI} - \mathbb{Z})$
- Geometry dependent bulk-boundary correspondence
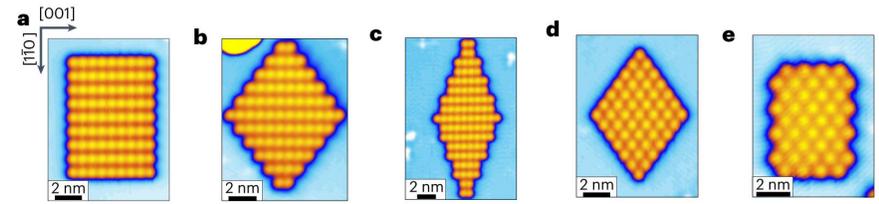

$\nu = 0$
$\nu = -2$
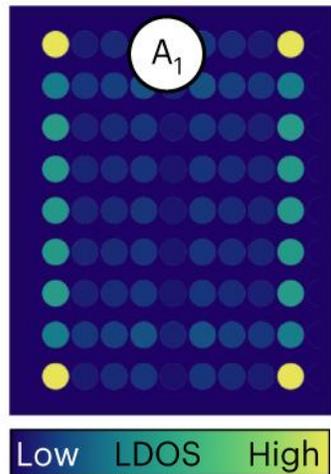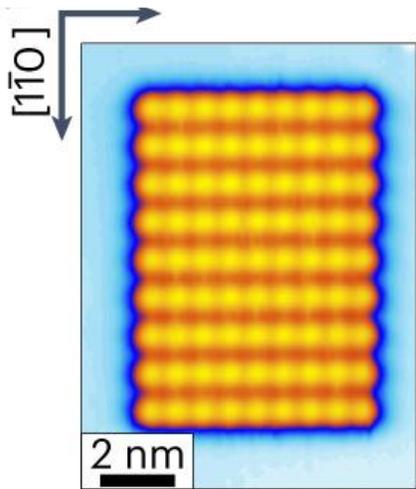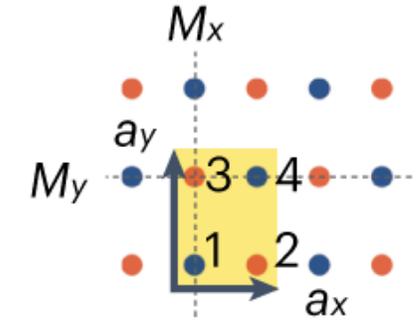
Zero energy DOS

$$H(\mathbf{k}) = \begin{pmatrix} 0 & q(\mathbf{k}) \\ q^\dagger(\mathbf{k}) & 0 \end{pmatrix},$$

$$\nu = -\frac{i}{2\pi} \int_{-\pi}^{\pi} dk \, \mathrm{Tr}[q^\dagger(k)\partial_k q(k)],$$
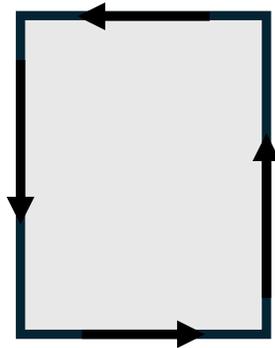
Take home messages

but not last slide

- Lattice terminations play a role in the emergence of distinct boundary modes

- If crystal symmetry is involved, a geometry dependent bulk–boundary correspondence arises

This does not hold always

Example: