JANUARY 2024

TEXAS
The University of Texas at Austin

SCRATCHING THE SURFACE: ATOMIC-SCALE INVESTIGATIONS WITH THE SCANNING PROBE MICROSCOPE

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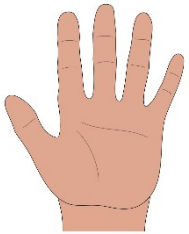
Nano Electronic Materials Research Group, The University of Texas at Austin

What is the ‘human instrumentation’?

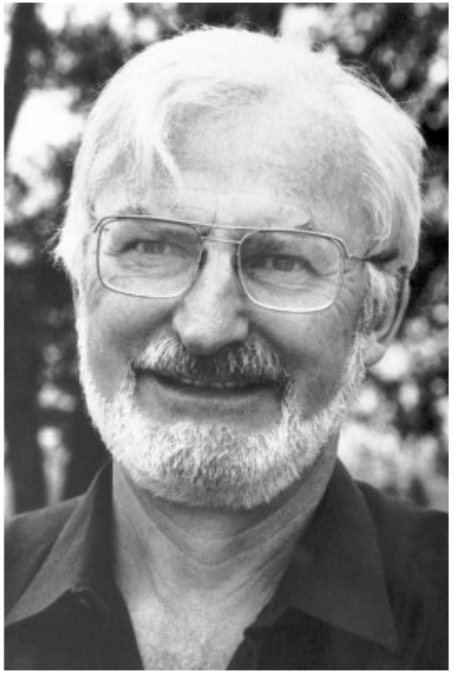
~380 – 700nm

~20 – 20,000 Hz



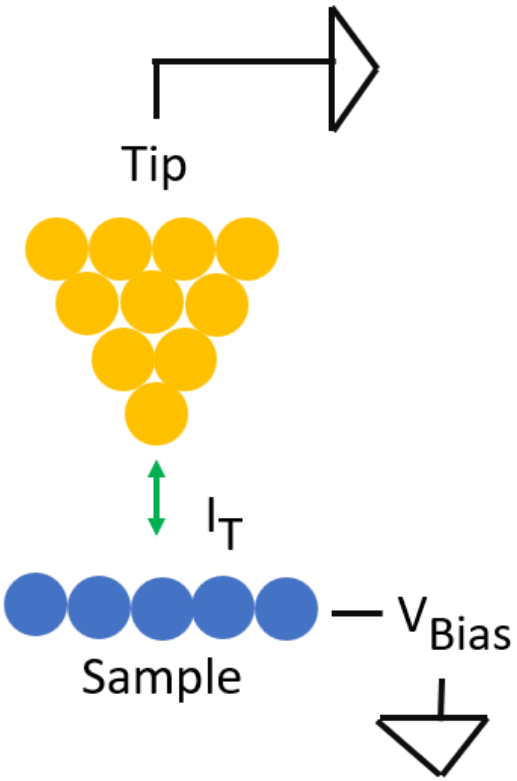
~0.01mm

Can we ‘touch’ atoms?



Nobel Prize, 1986

The Scanning Tunneling Microscope



Bias-Dependance

$$I \propto \int_{E_F}^{E_F+eV} n_t(\epsilon - eV) n_s(\epsilon) T(\epsilon, eV) d\epsilon$$

Decay into Vacuum

$$I \propto e^{-2\kappa z} \qquad \kappa = \sqrt{2m\phi + k_{\parallel}^2}/\hbar$$

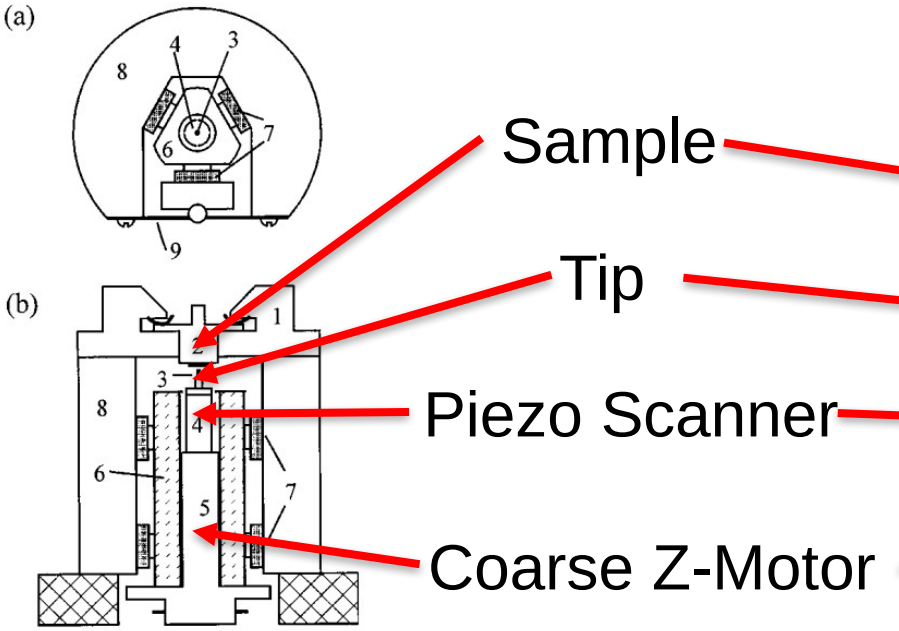
Differential Conductance:

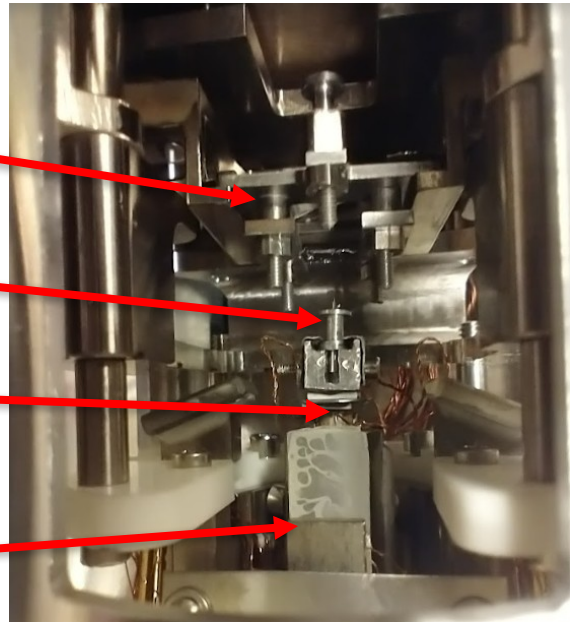
$$\frac{dI}{dV} \propto n_s(E_F + eV)$$

[2] Chen, *Introduction to Scanning Tunneling Microscopy*

The First STM…

…Improving the design…



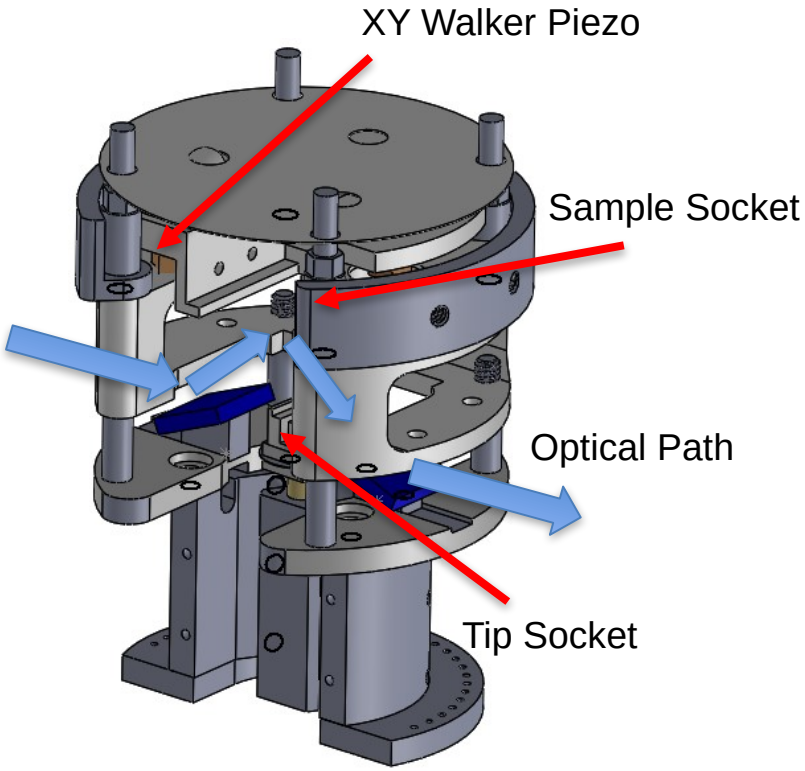


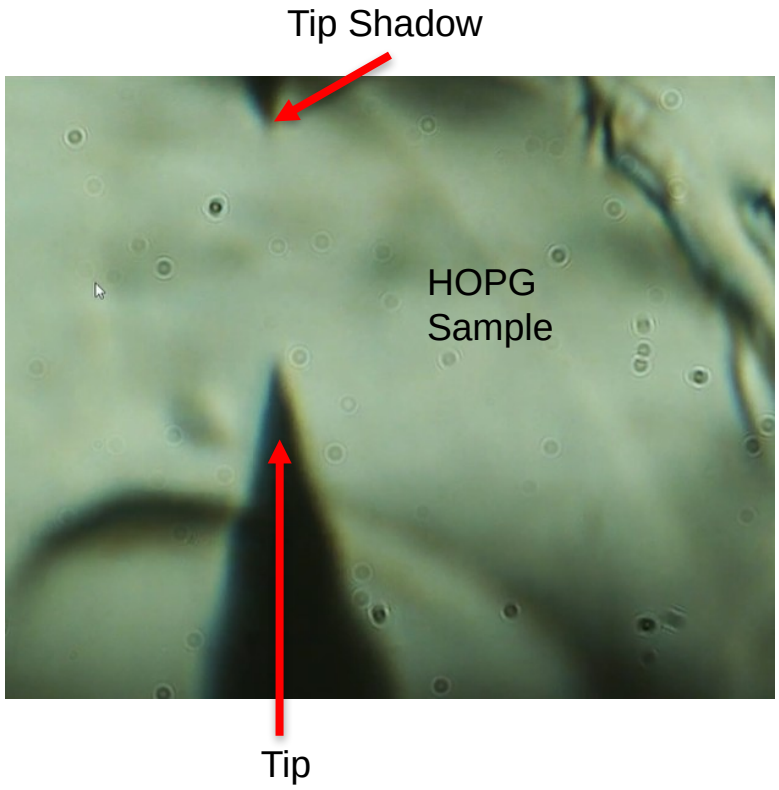
STM Head Designed by S.H. Pan

STM Head Designed by A. Murphy

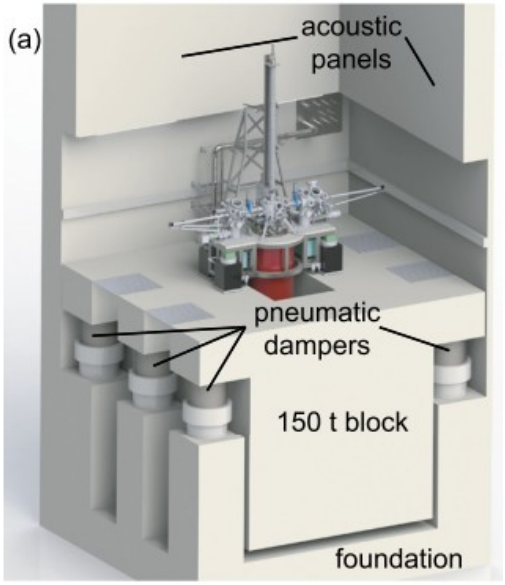
[3] S.H. Pan et al. Rev. Sci. Instum 70, 2 (1999)

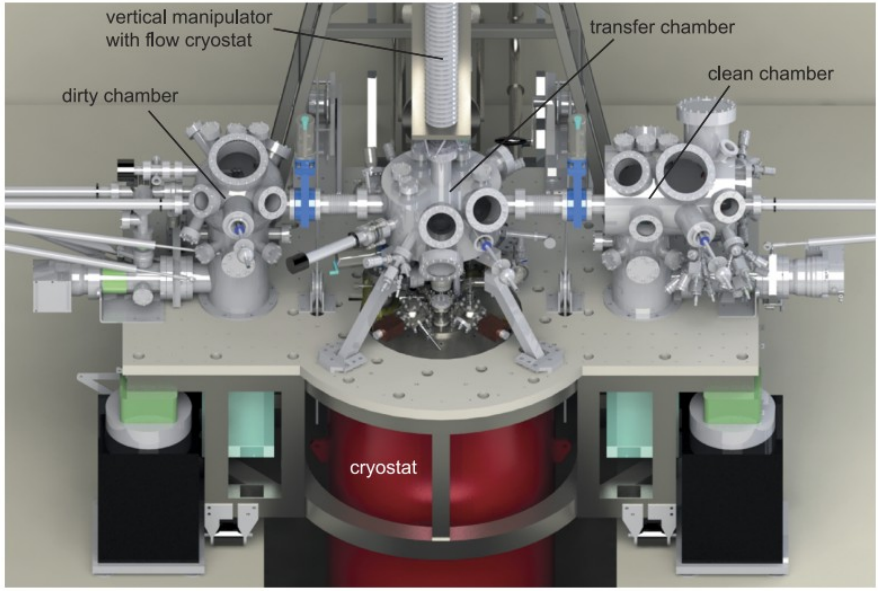
An STM with coarse XY Positioning

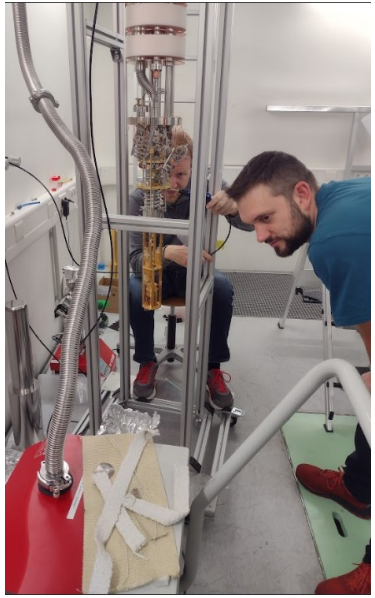




…State of the Art: Radboud University

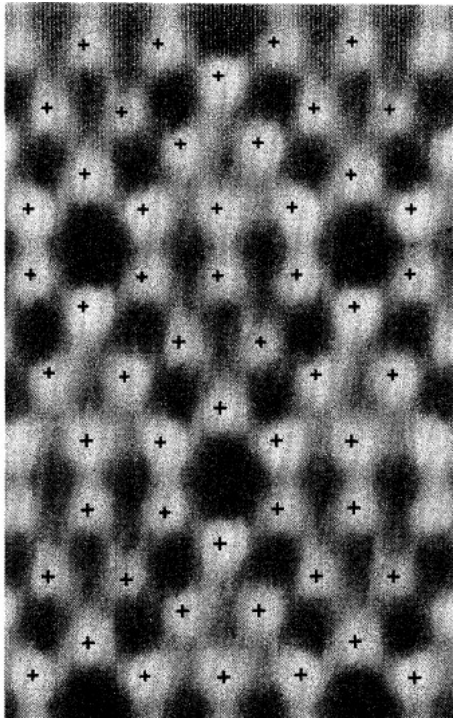




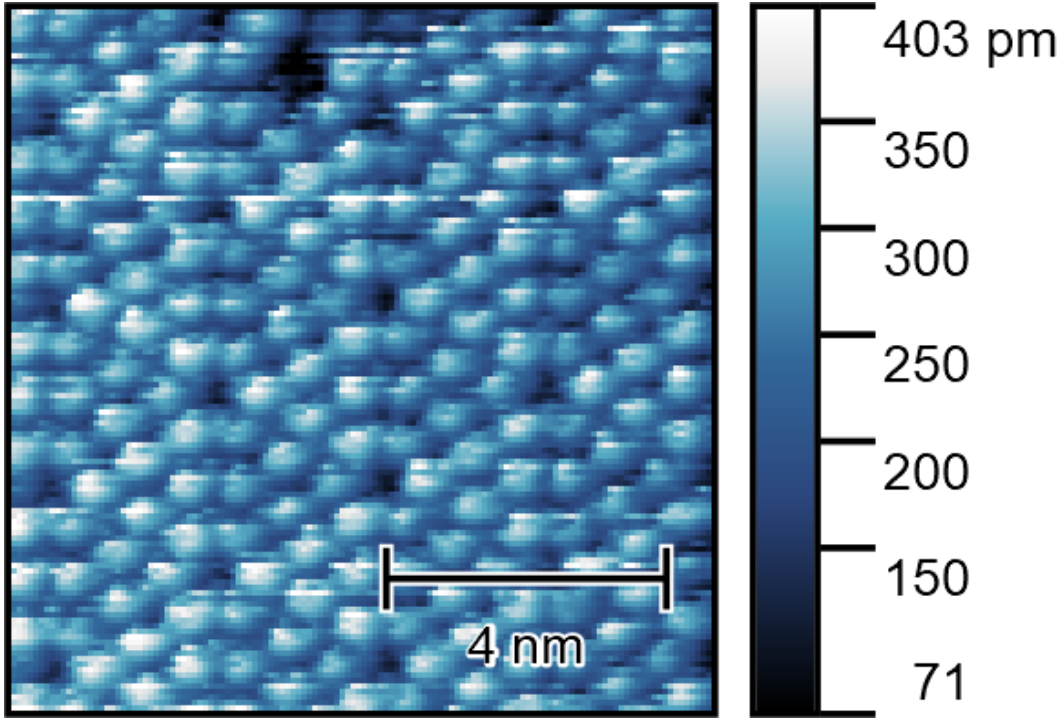


Rev. Sci. Instrum. 89, 033902 (2018)

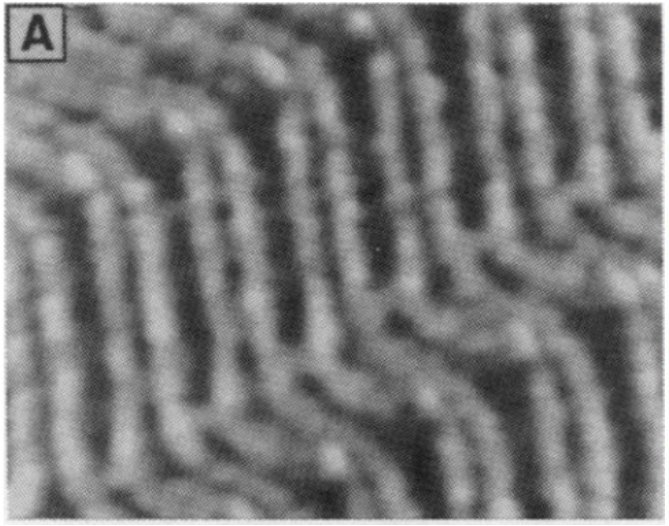
Imaging Atoms with STM…



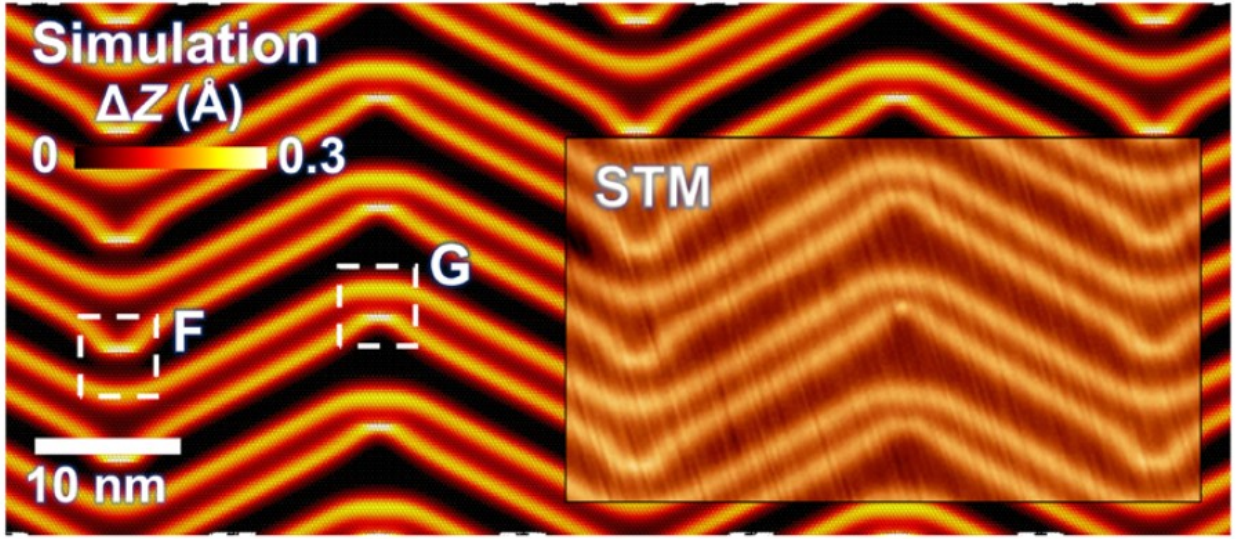
Phys. Rev. Lett. 50, 120 (1983)



Interesting Surface Reconstructions….

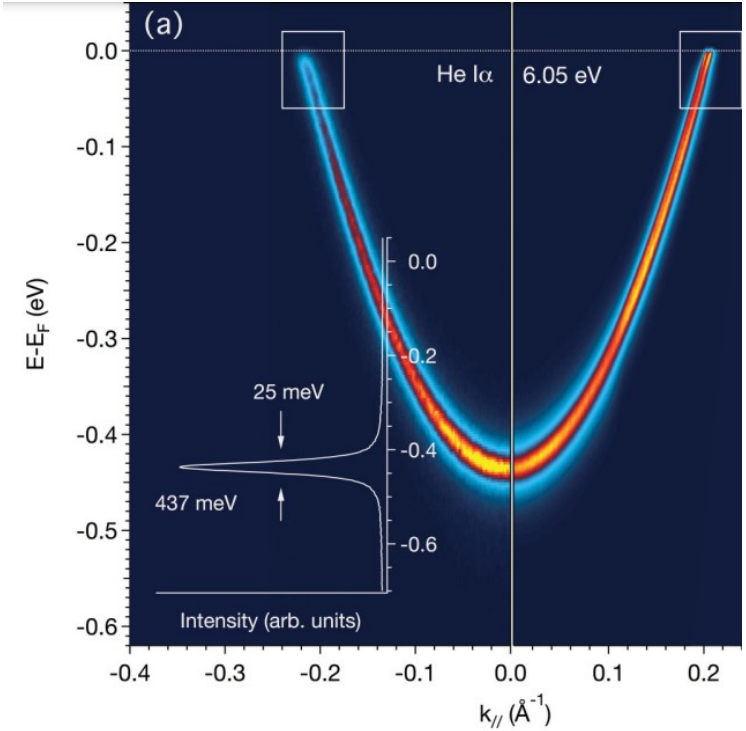


Science258,1763-1765(1992)

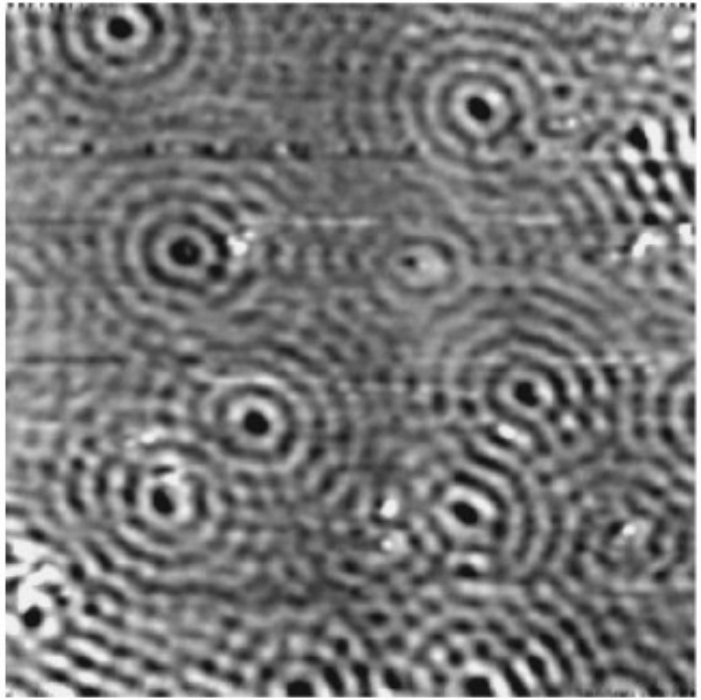


Sci. Adv.8,eabq2900(2022)

Surface States

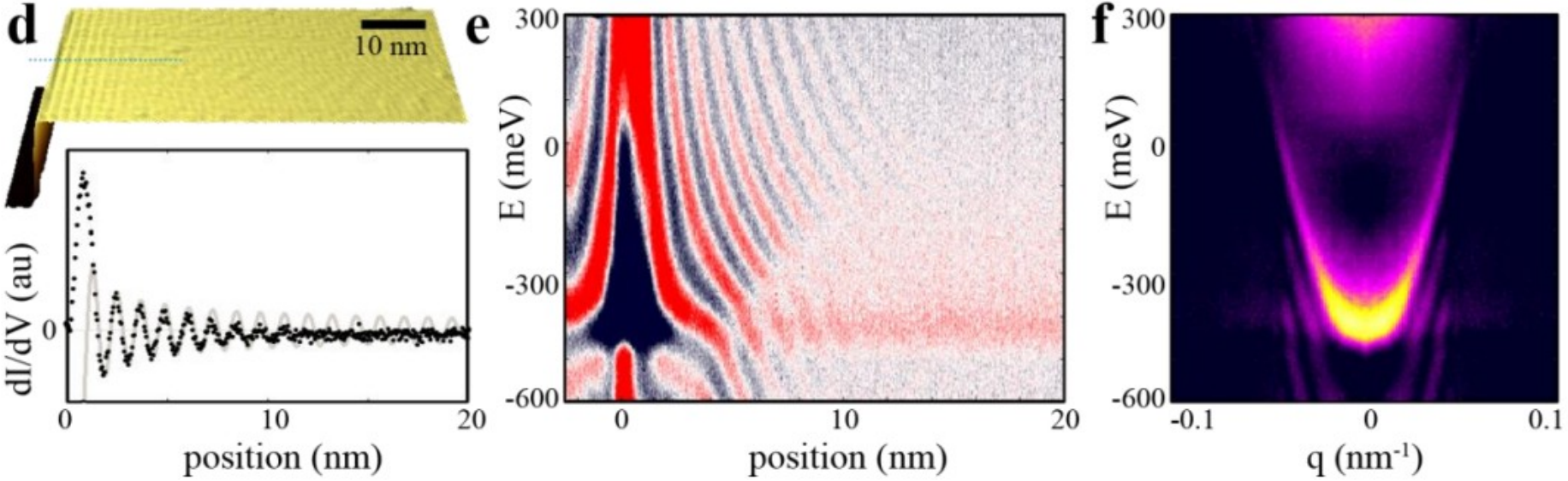


PRB 87, 075113 (2013)



Phys. Rev. B 58, 7361 (1998)

Quasi-Particle Interference



arXiv:2108.13635

Manipulating Atoms

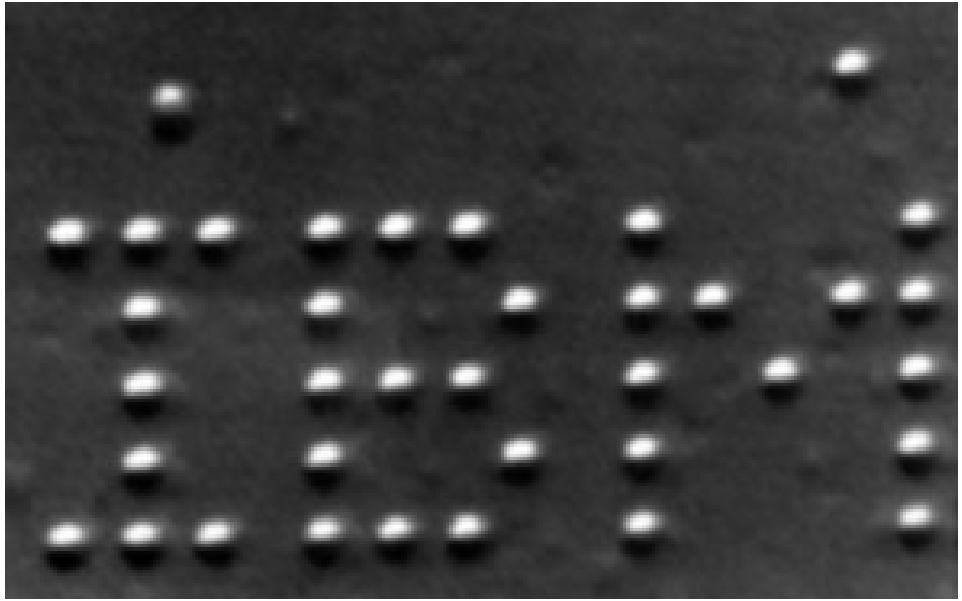
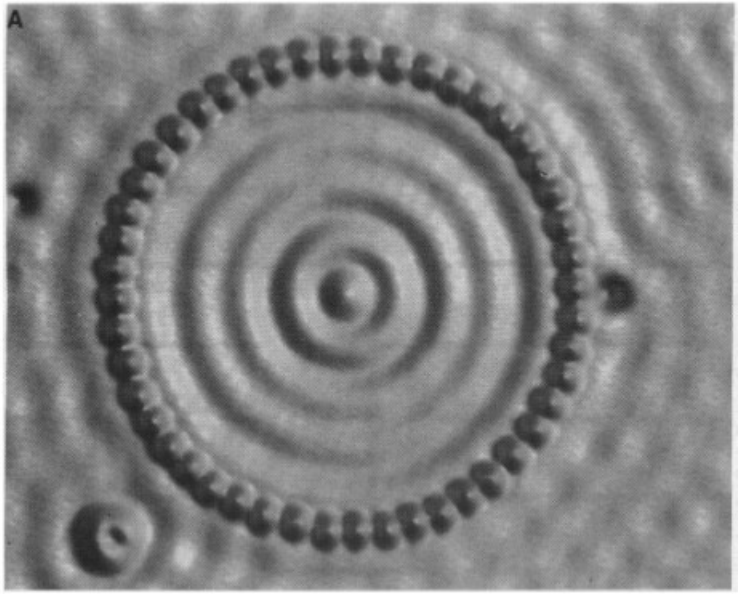
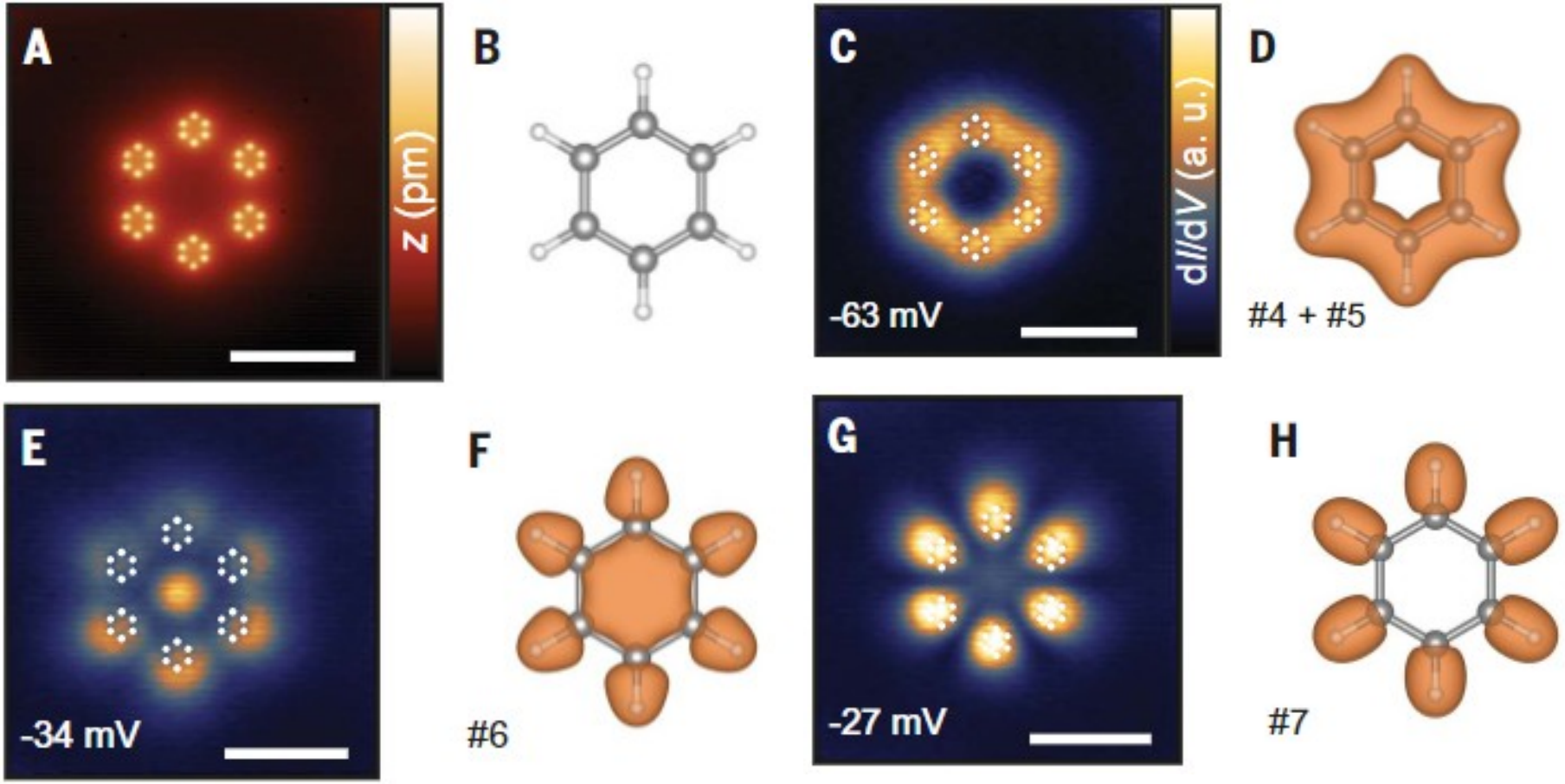


Image: IBM



Science 262, 218-220(1993)



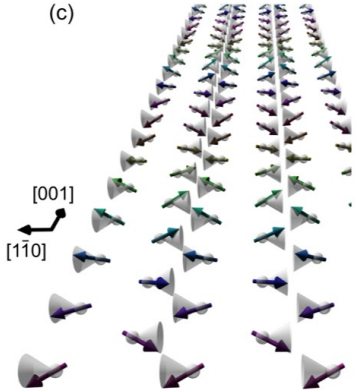
Science380,1048-1052(2023)

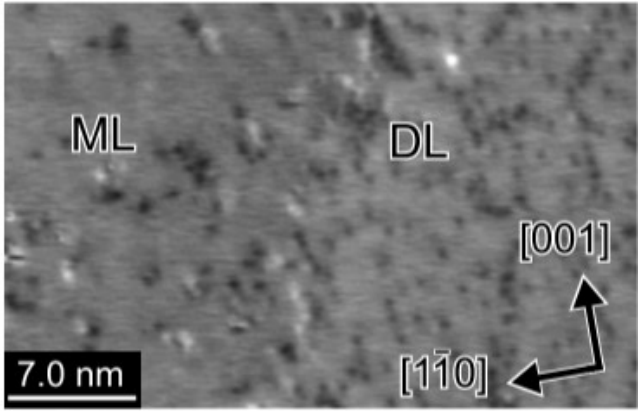
What About Spin?

- Magnetic Materials ⇨ Transmission coefficient is spin-dependent
- Magnetic tip (e.g. Cr, Fe, Ni) acts as spin-valve

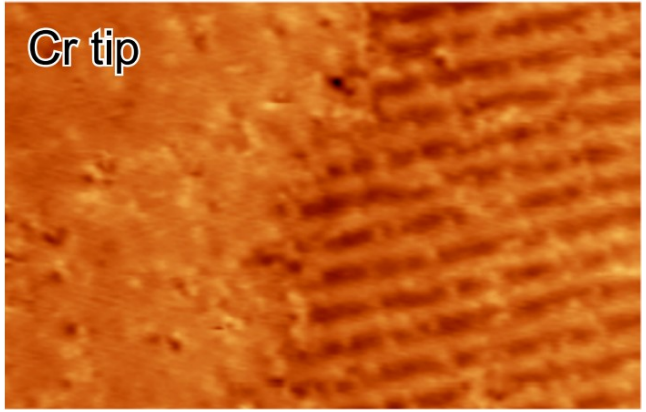
$$\Delta_{\uparrow\downarrow} I \propto \cos\theta$$

- Contrast between aligned/anti-aligned spin ⇨ In-plane vs. out-of-plane sensitivities





Topography



dI/dV @ -40mV

[4] Rev. Sci. Instrum. 90, 013704 (2019)

Atomic Force Microscopy

-Short-range repulsive forces, long range attractive forces

-Frequency Modulated AFM: Quartz tuning fork excited at natural frequency

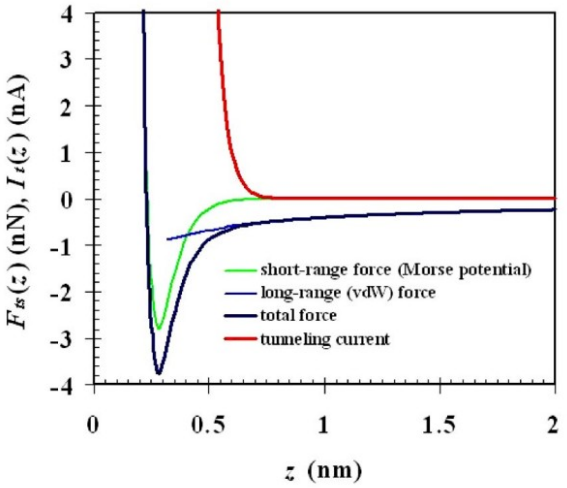
$$f = f_0$$

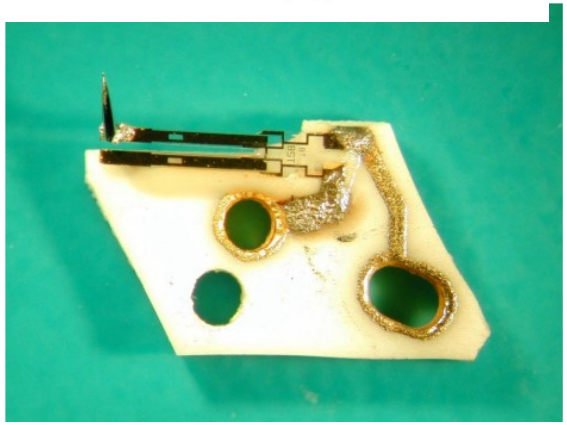
-Tip-sample interactions → frequency shift

$$f = f_0 + \Delta f,\ \Delta f = \frac{k_{ts}}{2k} f_0$$

where

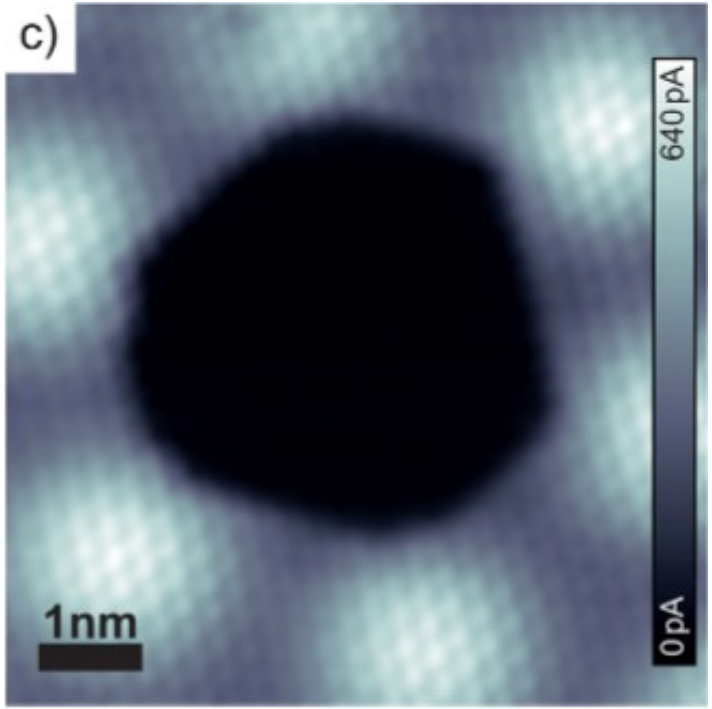
$$k_{ts} = \partial^2 U_{ts} / \partial z^2$$



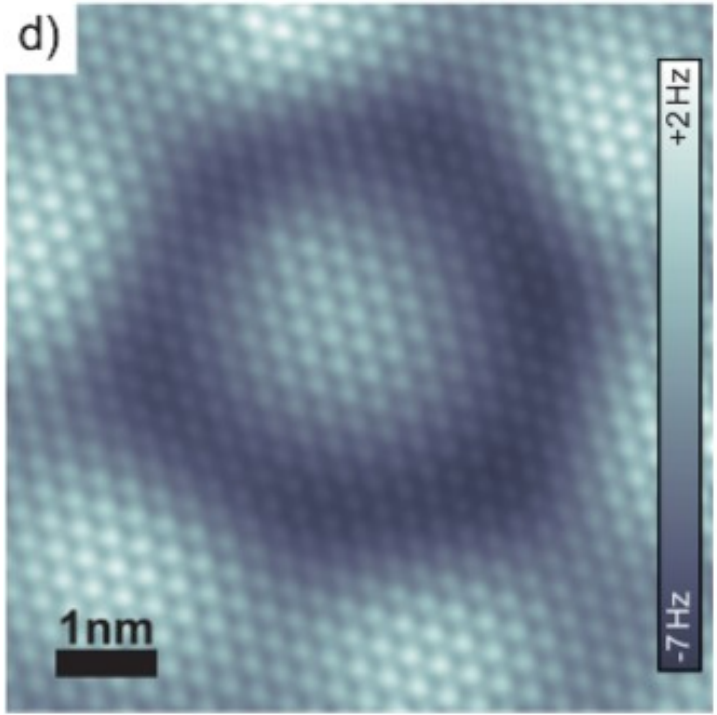


[3] Giessibl, Rev. Mod. Phys., 75, 3 (2003)

STM



AFM

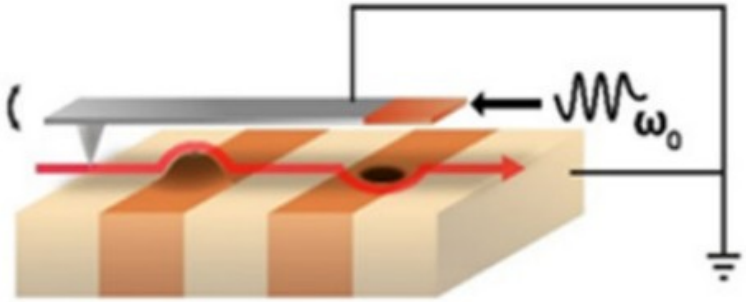


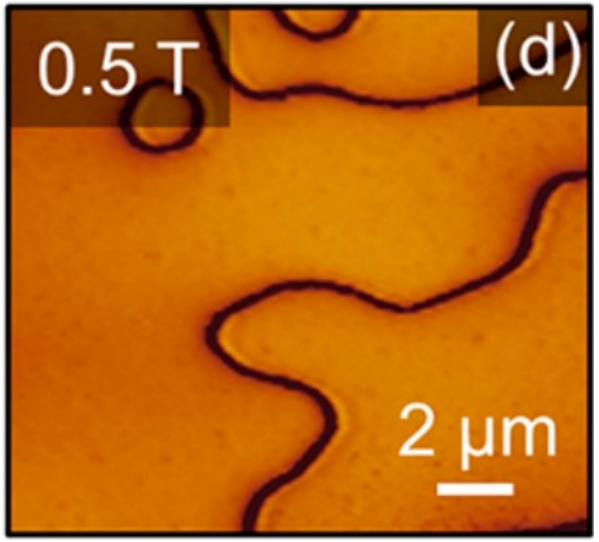
Nano Lett. 2016, 16, 8, 5163–5168

Magnetic Force Microscopy (MFM)

Long-range dipole interaction:

$$U_{dipole} = -\boldsymbol{\mu}_t \cdot \boldsymbol{B}_s$$





[5] Nano Lett. 2020, 20, 2609−2614

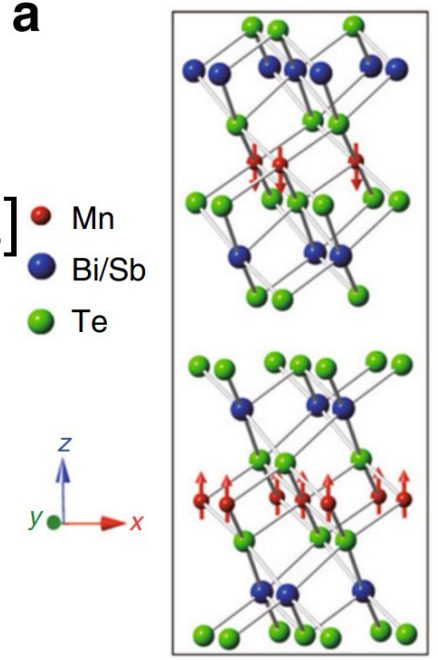
$MnBi_2Te_4$ Family – Intrinsic Magnetic Topological Insulator

- Septuple Layer VdW: Te-Bi-Te-Mn-Te-Bi-Te

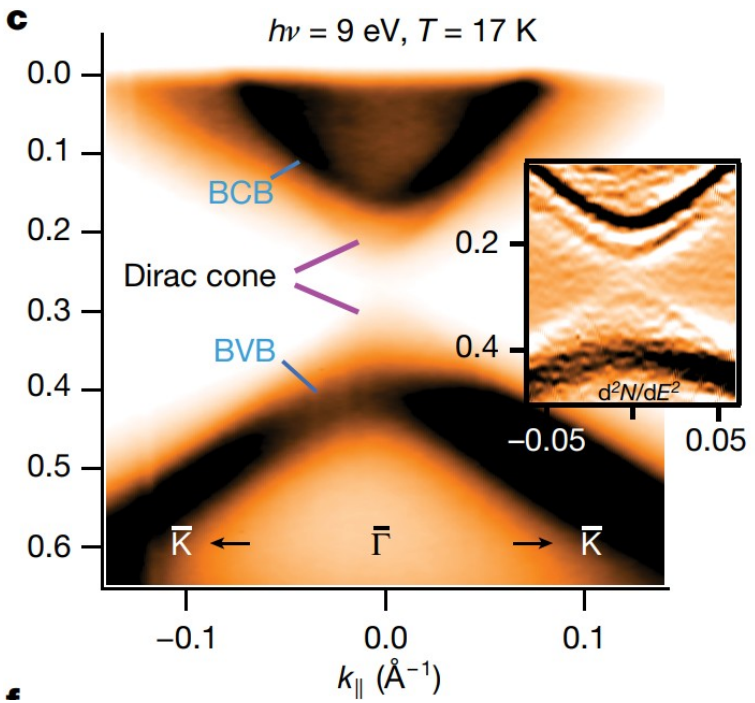
-A-Type AFM in [0001] Direction (T_N = 25K)

-Z_2 Classification:
$S = \Theta T_{1/2}$

-Predicted gapped (0001) Surface

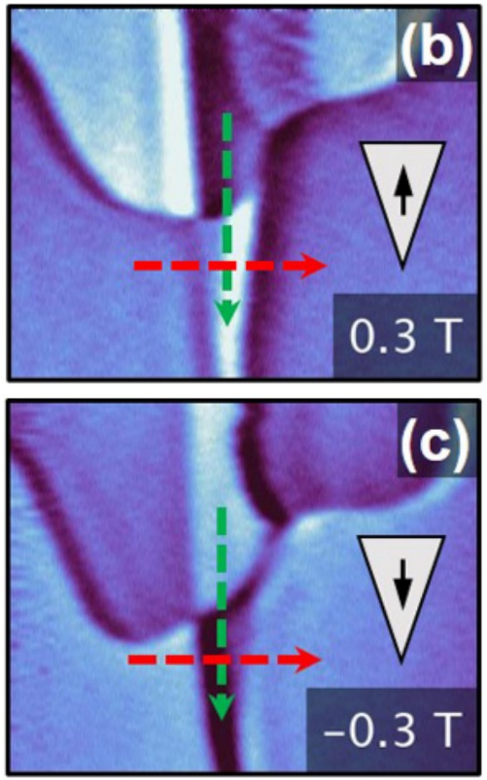


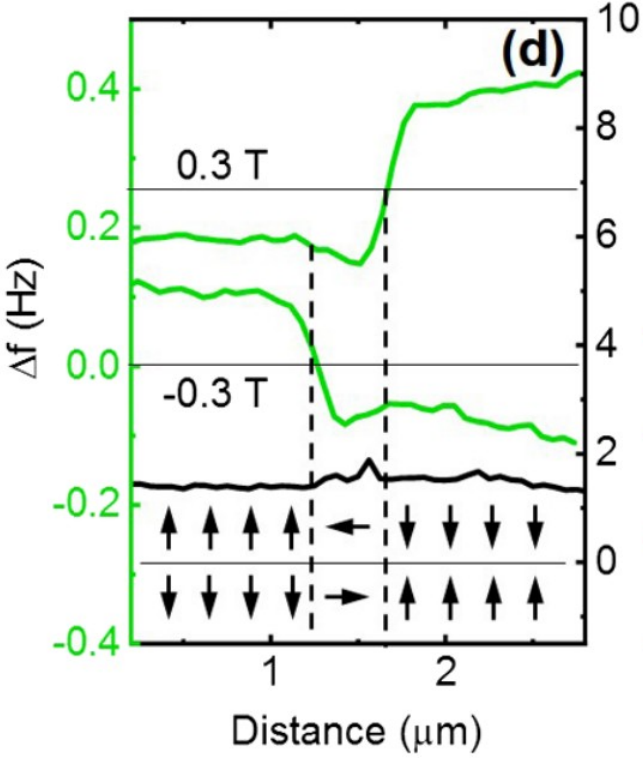
[10] Nat. Comm. 10, 4469 (2019)

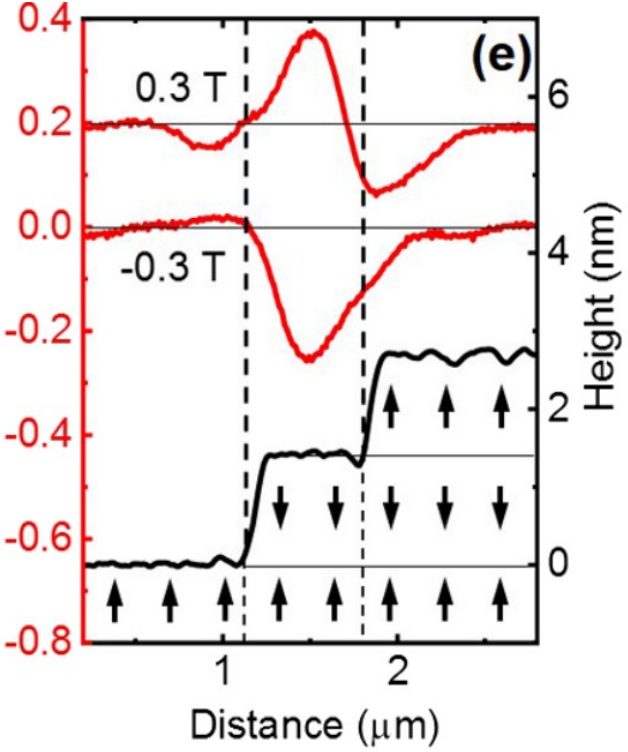


[11]Nature 576, 416–422 (2019)

What is the Magnetic Order at the Surface?





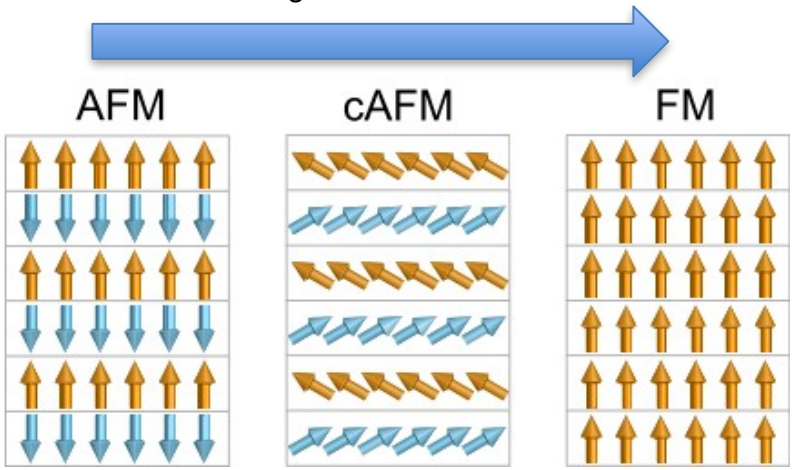


[12] PRL 125, 037201 (2020)

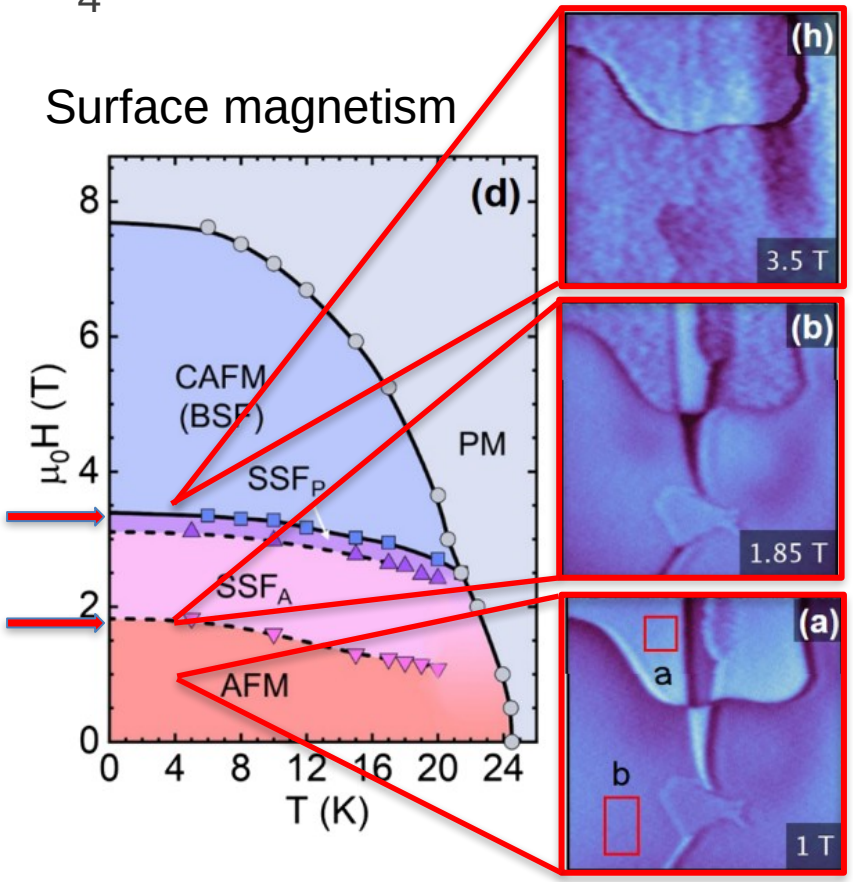
Magnetic Phases of $MnBi_2Te_4$

Bulk Magnetism

Increasing External Field



Surface magnetism

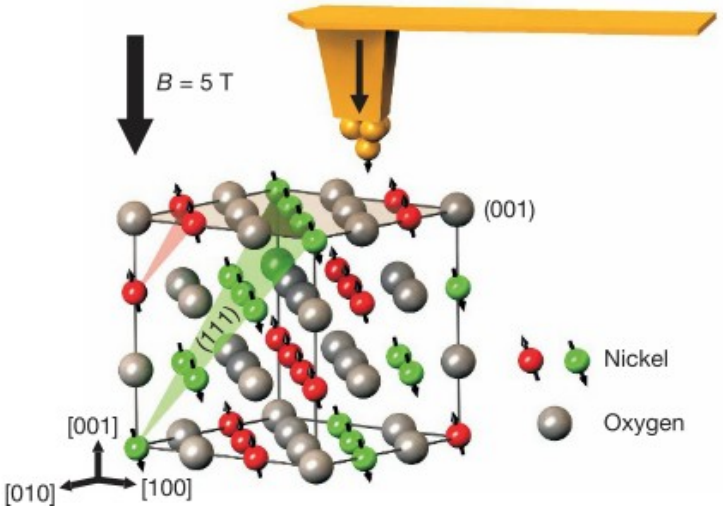


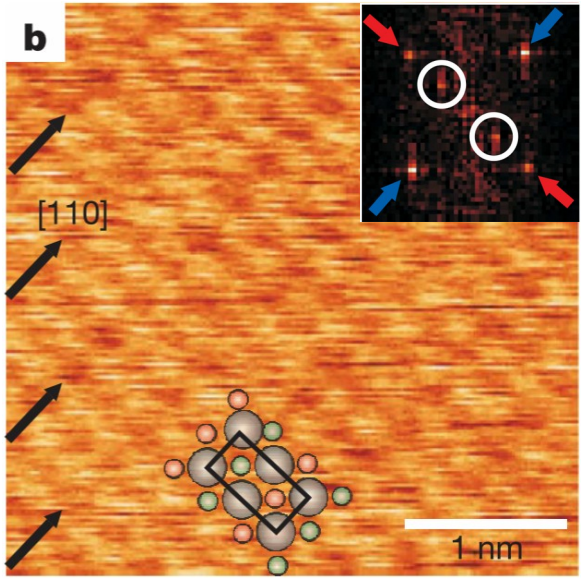
[12] PRL 125, 037201 (2020)

Magnetic Exchange Force Microscopy (MExFM)

Short-Range Exchange Interaction:

$$H_{ex} = J_{ts}(\boldsymbol{S}_t \cdot \boldsymbol{S}_s)$$





[6] Nature, 446, 29 (2007)

Thank you!