How to reveal atomic-scale magnetic order with scanning probe microscopes

Stefan Heinze

Interdisciplinary Nanoscience Center Hamburg and
Institute of Applied Physics, University of Hamburg, Germany

In recent years, spin-polarized scanning tunneling microscopy (SP-STM) has been established as a technique to resolve magnetic nanostructures down to the atomic scale [1-4]. Very recently, it has even become possible to measure the exchange interactions between tip and sample by magnetic exchange force microscopy (MExFM) [5,6]. However, the interpretation of such measurements is non-trivial, especially on the atomic scale. For SP-STM there are various contributions to the tunneling current from structural, electronic, chemical, and magnetic sample properties. For MExFM there are many basic open questions concerning e.g. the influence of tip material, structure, and sample systems on the size, sign, and distance dependence of exchange forces. Successful interpretation approaches for both techniques rely on an accurate description of the electronic structure of tip and sample and their interaction making density functional theory (DFT) an indispensable tool.

Here, I will present the theory of SP-STM and explain how one can reveal collinear and non-collinear magnetic order on the atomic scale [1-4]. This allows us to verify theoretical predictions based on DFT such as two-dimensional antiferromagnetism [1] or spin-spiral structures driven by the Dzyaloshinskii-Moriya interaction [3,4]. Surprisingly, it is even possible to image non-collinear atomic-scale magnetic order using a *non-magnetic* tip as the electronic structure changes slightly from atom to atom due to spin-orbit coupling. Finally, I will show how the antiferromagnetic order of Fe on W(001) can be resolved by MExFM and discuss how the structure and chemical composition of the tip influence the measured forces [6,7].

[1] A. Kubetzka *et al.*, Phys. Rev. Lett. **94**, 087204 (2005).
[2] K. von Bergmann *et al.*, Phys. Rev. Lett. **96**, 167203 (2006).
[3] M. Bode *et al.*, Nature **447**, 190 (2007).
[4] P. Ferriani *et al.*, Phys. Rev. Lett. **101**, 027201 (2008).
[5] U. Kaiser *et al.*, Nature **446**, 522 (2007).
[6] R. Schmidt *et al.*, submitted.
[7] C. Lazo *et al.*, submitted.