IM1.P13
Optimizing spin detection in TEM – From imaging to quantum metrology

S. S. Beltrán Romero[1,2], M. Gaida[3], S. Löffler[1,2], S. Nimmrichter[3], D. Rätzel[1,4,2], P. Haslinger[1,2]

[1]Technical University of Vienna, Vienna, Austria
[2]Technical University of Vienna, University Service Centre for Transmission Electron Microscopy, Vienna, Austria
[3]University of Siegen, Siegen, Germany
[4]University of Bremen, ZARM, Bremen, Germany

Introduction: Transmission Electron Microscopy (TEM) has revolutionized nanoscale research by enabling unprecedented simultaneous spatial and temporal resolution thanks to advancements such as aberration correction as well as cryogenic and ultra-fast techniques. However, the ability of TEM to probe spin dynamics—essential for understanding quantum materials—remains limited. Recent innovations in microwave spectroscopic tools [1,2] suggest new possibilities for overcoming these limitations.

Objectives: We present a study on spin imaging capabilities in time-resolved TEM and methods for their enhancement. Specifically, we investigate the feasibility of imaging many-spin samples under parallel illumination with an unpolarized beam, optimize measurement conditions using Quantum Metrology, and explore the fundamental limits of spin detection through imaging and diffraction analysis.

Materials & Methods: We employ a framework based on scattering theory to model spin sample probing with time-resolved TEM. Our approach accounts for both elastic and inelastic processes, including electron backaction on the spin [3]. Using the Classical Fisher Information (CFI), we optimize measurement conditions for spin detection, comparing imaging and diffraction modes, as well as different defocus planes. An optimized image analysis pipeline is applied to maximize the CFI, and we discuss the attainability of the Quantum Fisher Information (QFI) limit for single magnetic dipole imaging.

Results: Our simulations reveal how the choice of measurement setup influences the magnetic dipole detection precision. We identify optimized conditions that enhance Signal-To-Noise Ratio (SNR) and contrast, significantly improving the sensitivity of TEM-based spin imaging. In particular, diffraction mode provides a major advantage, as the cumulative deflection from multiple spins enhances the detectable signal, especially at low deflection angles.

Conclusion: Our work establishes a theoretical foundation for integrating spin resonance techniques with advanced microscopy analysis tools. By optimizing imaging strategies and exploring the fundamental metrological limits of spin detection, we pave the way for breakthroughs in atomic-scale spin imaging and manipulation.

References

[1] P. Haslinger, S. Nimmrichter, and D. Rätzel, *Spin resonance spectroscopy with an electron microscope*, Quantum Science and Technology 9, 035051 (2024).

[2] Antonín Jaroš, Johann Toyfl, Andrea Pupić Benjamin Czasch, Giovanni Boero, Isobel C. Bicket, and Philipp Haslinger, *Electron spin resonance spectroscopy in a transmission electron microscope*, arXiv:2408.16492 (2024).

[3] D. Rätzel, D. Hartley, O. Schwartz, and P. Haslinger, *Controlling Quantum Systems with Modulated Electron Beams*, Phys. Rev. Research 3, 023247 (2021).