Controlling and Sensing Spin Systems with Free Space Electrons

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Coherent control and detection of quantum systems lie at the heart of quantum optics and quantum technologies. While optical and microwave control techniques are well established, the use of free-space electron beams as both manipulator and sensors opens an entirely new regime for spatial resolution and spectroscopic access.

In this talk, I will first outline intuitively our theoretical work [1] showing how the non-radiative near-fields of temporally modulated free-space electron beams can coherently drive quantum systems. I show that such manipulation can be performed with only classical control over the electron beam itself and that potential challenges like shot noise and decoherence through back action on the electrons are for certain parameter ranges insignificant for our approach. I will discuss possible implementations and show preliminary data on manipulating spin systems in a sample.

I will then present our recent experimental setup on SPINEM (Spin Electron Microscopy) [2], which integrates continuous-wave electron spin resonance (ESR) spectroscopy directly into a transmission electron microscope. By combining a custom microwave resonator with a free space electron beam [3], we achieve in-situ, phase-locked detection of microwave-driven spin precession with *picoradian* deflection sensitivity (~280 prad) and spatial mapping capabilities down to 30 µm. This approach directly senses the magnetic fields generated by precessing spins in the GHz regime, enabling localized spin spectroscopy in a TEM.

I will conclude with perspectives on pushing SPINEM towards atomic resolution and single-spin sensitivity [4]. These advances could open new frontiers in nanoscale spintronics, magnonics, and quantum materials research, and provide an electron-based analogue to magnetic resonance imaging at the level of individual nanostructures.

References

[1] D. Rätzel, D. Hartley, O. Schwartz, and P. Haslinger, *Controlling Quantum Systems with Modulated Electron Beams*, Phys. Rev. Res. **3**, 023247 (2021).
[2] A. Jaroš, J. Toyfl, A. Pupić, B. Czasch, G. Boero, I. Bicket, P. Haslinger *Sensing Spin Systems with a Transmission Electron Microscope*, arXiv:2503.06761
[3] A. Jaroš, M. Seifner, J. Toyfl, B. Czasch, I. Bicket, P. Haslinger, *Electron Spin Resonance Spectroscopy in a Transmission Electron Microscope*, arXiv:2408.16492
[4] P. Haslinger, S. Nimmrichter, D. Rätzel, *Spin Resonance Spectroscopy With an Electron Microscope*, QST, **9**, 035051 (2024).