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The Surprising Dynamics of Electron Vortex Beams

Stefan Löffler[1,2,3], Thomas Schachinger[2,3], Michael Stöger-Pollach[2], Peter Schattschneider[3,4]

[1] Department of Materials Science and Engineering, McMaster University, Hamilton, Canada.
[2] University Service Centre for Transmission Electron Microscopy, Vienna University of Technology, Vienna, Austria.
[3] Institute of Solid State Physics, Vienna University of Technology, Vienna, Austria.
[4] Ecole Centrale Paris, Chatenây-Malabry, France.

Vortex structures were predicted for light optical beams in 1974 [1] and experimentally realized two decades later. Shortly after the discovery of vortex electrons [2], free electrons with quantized angular momentum could routinely be produced with the holographic mask technique [3]. Owing to their short wavelength, these matter waves can be focused to atomic size. Another novel aspect is their magnetic moment $\mu_B\, m$ quantized in multiples of the Bohr magneton, independent of the spin polarization. Both features make them extremely attractive as a nanoscale probe for solid state physics.

The theory of electron vortex dynamics is well developed [4-7]. The most intriguing prediction is a quantized rotation of electron vortex beams under certain conditions – when they represent free electron Landau states – including zero- and cyclotron (double-Larmor)-rotation. It is caused by the Landau-Zeeman phase acquired over a wave packet’s trajectory and is analogous to the image rotation of optical beams caused by a Berry phase.

This is in obvious contradiction to standard electron optics that predicts Larmor image rotation in the magnetic lens field of a TEM. Recently, this contradiction could be unraveled by extending the theoretical model [6] to diffracting Laguerre Gaussian modes. It was shown that the peculiar rotational dynamics of electron vortices can be explained by a combination of slow Larmor- and fast Gouy rotations and that the Landau states naturally occur in the transition region in between the two extrema. This generalized description is confirmed by experimental data showing an extended set of peculiar rotations, including zero, cyclotron-, Larmor- and rapid Gouy-rotations all present in one single convergent electron vortex beam. Experiments were performed borrowing a method from visible light optics, namely obstructing half the vortex ring and observing the inclination of the shadow image of the edge when it propagates through the magnetic field of the lens. The rotation dynamics can be cast into a dimensionless universal form covering four orders of magnitude of angular frequency (Fig. 1).

An important aspect of vortex beams is their propagation in matter. It can be shown that they are topologically protected when centered on an atomic column [8], and that they exchange orbital angular momentum with the medium (Fig. 2).

Finally, we study the spin-orbit interaction of vortex electrons propagating in the magnetic field of the objective lens in a TEM. It turns out that such a beam, being post-selected on axis in the far field, acts as a perfect spin filter in the limit of infinitely small detectors. Increasing the detector size, the polarization decreases rapidly, dropping below 10^{-4} for realistic setups. It has to be seen to which extent this figure of merit can be improved by optimizing parameters such as voltage and convergence angle.

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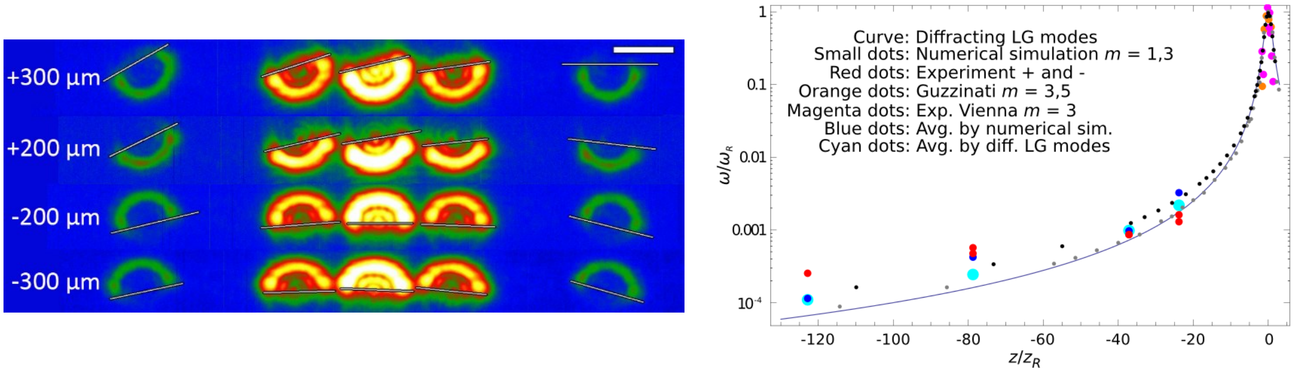

Fig. 1: Left: Experimental images of the vortex rotation dynamics. The scale bar is 20 nm. Right: Universal dimensionless rotation dynamics in a magnetic field along the z axis, scaled by the Rayleigh range z_R. Angular frequency in units of $\omega_R = v/z_R$, where v is the velocity of the electron.

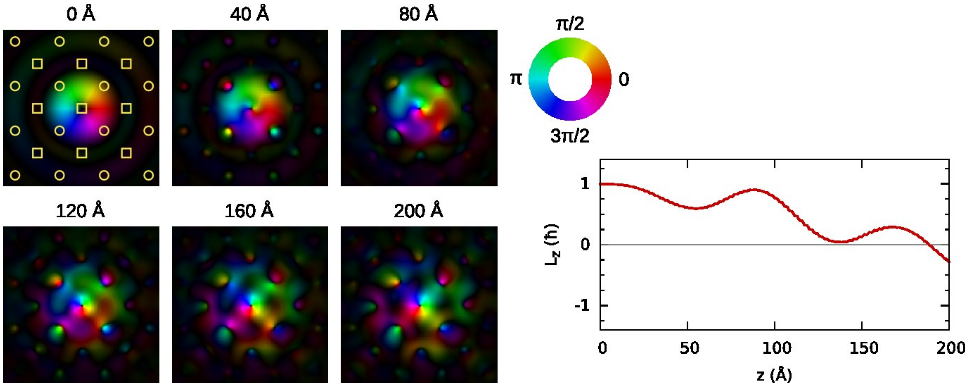

Fig. 2: Propagation of an m=1 vortex beam through a 20 nm thick Fe crystal in [0 0 1] orientation. The circles and squares mark atom positions in different layers of the sample. The curve shows the change of the expectation value of the orbital angular momentum of the vortex.