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Electron vortex propagation in the magnetic lens field

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Since it became possible to create electron vortex beams in transmission electron microscopes (TEM) [1, 2], it is very important to understand their motion, in particular in the magnetic lens fields in a TEM. These doughnut shaped beams carry quantized orbital angular momentum (OAM) of $L_z = m\hbar$ as well as a quantized magnetic moment of $M = \mu_B m$ per electron, which opens up the road for applications like particle manipulation [3] and mapping magnetic moments on atomic scales [4].

Standard electron imaging theory predicts that all objects traversing the magnetic lens fields in a TEM rotate with the same speed [5]. Recently, Bliokh et al. theoretically predicted peculiar rotations of electron vortex beams in uniform magnetic fields parallel to the beam axis [6]. They proposed that electron beams consisting of a coherent superposition of vortices with different orbital angular momentum show different rotation speeds in the presence of a vector potential as created, e.g., by the objective lens in a TEM. In particular, depending on the sign of the scalar product $B \cdot M$ where B is the z-component of the lens field and M is the net magnetic moment of the vortex, cyclotron (double-Larmor) rotation or no rotation is expected. Vortices with $M = 0$ should show Larmor rotation.

In this work, we present a series of experiments to investigate these peculiar rotations. To be able to experimentally observe these azimuthal rotations, one has to break the radial symmetry of the vortex beams [7]. We used a sharp edge made by breaking a Si crystal, which was then shifted in z-direction (see Figure 1.). As the blocking edge is moving through the lens field, different rotation angles of the cut vortices were observed (see Figure 2.). The acquired rotation angle over the z-shift distance then gives the azimuthal rotation speed of the vortex electrons. To avoid contributions from the superimposed Gouy rotation, we used the C_2 lens to defocus the electron beams to a point far outside the Rayleigh range [7, 8]. By that, we observed a variety of different rotation speeds, strongly depending on the C_2 defocus, as well as the vortex order m (see Figure 3.).

To better understand this complex behavior, we performed numerical ray tracing calculations using the classical Lorentz force and realistic parameters for the objective lens field. The simulation results are in good agreement with the experimental data as is shown in Figure 2. The remaining discrepancies between theory and experiment are attributed to the inhomogeneous lens field and the imperfect blocking edge.

We found an extended set of peculiar rotations of electron vortex beams in TEM, including zero, Larmor and cylclotron frequency at a certain C_2 defocus value and vortex order m. These findings put the general theorem of Larmor rotation in a TEM in question and necessitate the reevaluation of the applicability of the established theory of imaging in a TEM.

1. M. Uchida and A. Tonomura, Nature 464 (2010), 08904.
2. J. Verbeeck, H. Tian and P. Schattschneider, Nature 467 (2010), 09366.
3. J. Verbeeck, H. Tian and G. Van Tendeloo, Adv. Mat. 25 (2013), 1114.
4. P. Schattschneider, J. Verbeeck and V. Mauchamp, Phys. Rev. B 82 (2010), 144418.
5. W. Glaser, Grundlagen der Elektronenoptik, Springer-Verlag Wien,1952.
6. K. Y. Bliokh, P. Schattschneider and J. Verbeeck, Phys. Rev. X 2 (2012), 014011.
7. G. Guzzinatti, P. Schattschneider and K. Y. Bliokh, PRL 110 (2013), 093601.
8. S. M. Baumann, D. M. Kalb and L. H. MacMillan, Opt. Expr. 17 (2009), 9818.
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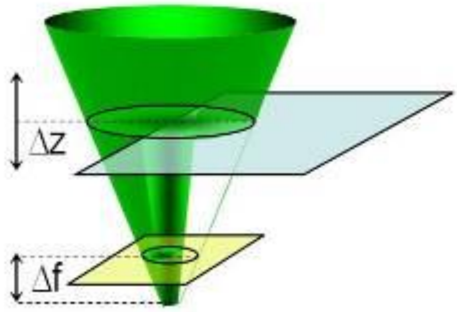

Figure 1. Sketch of the experimental setup (not to scale). Half of the incoming convergent electron beam (green) is blocked by a sharp Si knife edge (blue). The knife edge is then z-shifted from -375 µm to +375 µm in order to see the variation of the azimuthal cutting angle in the observation plane (yellow). Δ*f* is chosen in way that contributions from the Gouy rotation are minimized.

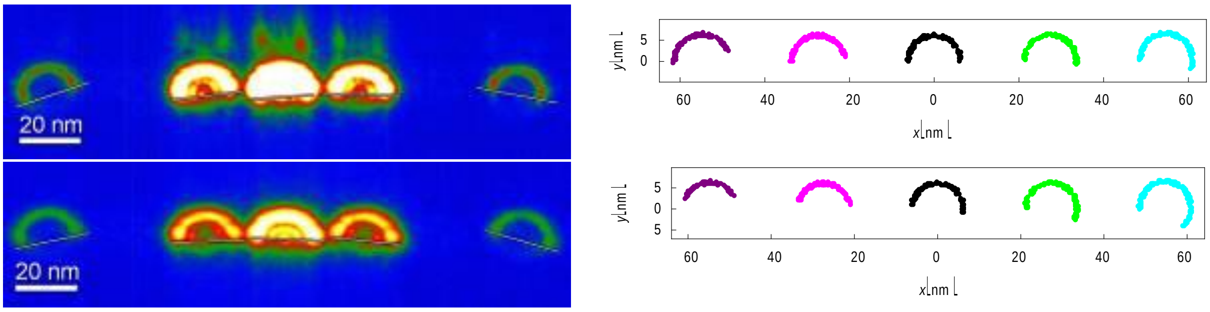

Figure 2. Left: Measurements of cut vortices, where the azimuthal rotation angle of vortices with topological charge *m* = 0, ±1, ±3 can be seen. The observation plane Δ*f* was 5.7 µm beneath the focused row of vortices and the z-shift value Δ*z* of the blocking edge was 100 µm under the observation plane for the upper row and 300 µm for the lower one. Right: Simulated electron distribution for the experimental parameters on the left side using the Lorentz force and realistic parameters for the objective lens field. The electrons' vorticities were added by assigning transverse velocity components according to $L_z = m_e \cdot (r_e \times v_e) = m\hbar$, where m_e, r_e, v_e are the electron's rest mass, radial distance to the optical axis and transverse velocity, respectively.

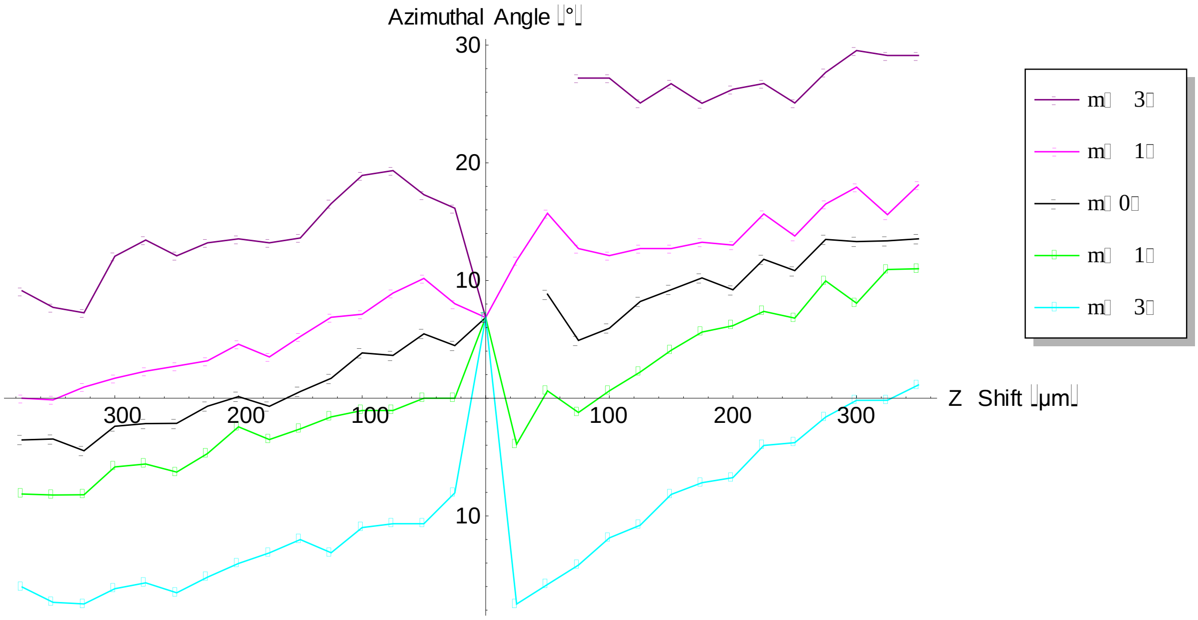

Figure 3. Diagram showing the experimentally observed azimuthal rotation angles over the knife edge's z-shift position for electron beams carrying topological charges *m* = 0, ±1, ±3 and for Δ*f* = 5.7 µm. The different rotation speeds can be discriminated by the increment of the azimuthal angle.