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Mode conversion, peculiar rotations, and the Landau-Zeeman-Berry phase in electron vortex beams

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Vortex beams are characterized by a spiraling wavefront and a phase singularity at the center. They were predicted for optical beams in 1974 [1] and experimentally realized two decades later. Today, there are many applications of optical vortices ranging from tweezers exerting a torque, over optical micromotors, cooling mechanisms, toroidal Bose-Einstein condensates to exoplanet detection [2]. Shorty after the discovery of vortex electrons [3], the holographic mask technique for routinely producing free electrons with quantized angular momentum was established [4]. Owing to their short wavelength, fast vortex electrons can be focused to atomic size. Another interesting aspect is their quantized magnetic moment, even without spin polarization. Both features make them extremely attractive as a novel probe in solid state physics. A technical problem is that the holographic masks drastically reduce the intensity in the outgoing vortex. Here, we describe a novel method for vortex production, based on astigmatic mode conversion [5]. It allows the generation of electron vortices with almost tenfold intensity, and at the same time provides easy detection of vorticity as shown in Figure 1. The theory of propagating electron vortices has been developed in a series of papers [6-8]. For non-diffracting Laguerre-Gaussian electron vortices, a peculiar rotation mechanism in a homo-geneous magnetic field is predicted. The important practical problem of how vortices behave in the lens fields of the TEM has not been tackled yet. Our analysis shows that coherent superpositions of vortices with different orbital angular momentum (OAM) show internal structure. This structure rotates in a homogeneous magnetic field with cyclotron, Larmor, or zero frequency, independent of the topological charge itself, but depending on the sign of the inner product between magnetic field and net angular momentum $\langle L \rangle$ of the vortex. The rotation can be shown to be caused by the *Landau-Zeeman* phase acquired over a wave packet's trajectory; it is analogous to the image rotation of optical beams caused by a Berry phase. Experimental results, using a blocking edge in the illumination system [9] as sketched in Figure 2, confirm the peculiar rotation of vortices with $\langle L \rangle$ - dependent frequency as shown in Figure 3. More involved ray-tracing simulations of convergent beams reveal rich details of vortex propagation that are not covered by the simplified description based on non-diffracting Laguerre-Gaussian modes; for details see reference [10]. Finally we discuss possible applications of Landau-Zeeman (or Berry) phases in electron microscopy, as well as the consequences of the peculiar rotation, seemingly challenging the paradigm of the co-moving Larmor coordinate system in electron optics [11].

1. J. Nye and M. Berry, Proceedings of the Royal Society of London, Series A 336 (1974), 165–190.
2. S. Franke-Arnold, L. Allen and M. J. Padgett, Laser Photonics Rev.2 (2008), 299.
3. M. Uchida and A. Tonomura, Nature 464 (2010), 737–739.
4. J. Verbeeck, H. Tian and P. Schattschneider, Nature 467 (2010), 301–304.
5. P. Schattschneider,M. Stöger-Pollach and J. Verbeeck, Phys. Rev. Lett. 109 (2012), 084801.
6. K. Y. Bliokh, Y. P. Bliokh, S. Savel'ev, and F. Nori, Phys. Rev. Lett. 99 (2007), 190404.
7. P. Schattschneider and J. Verbeeck, Ultramicroscopy 111 (2011), 1461.
8. K.H. Bliokh, P. Schattschneider, J. Verbeeck and F. Nori, Physical Review X 2 (2012), 041011.
9. G. Guzzinatti, P. Schattschneider, K. Y. Bliokh, F. Nori and J. Verbeeck, PRL 110 (2013), 093601.
10. T. Schachinger, MC2013.
11. W. Glaser, Grundlagen der Elektronenoptik, Springer-Verlag Wien,1952.
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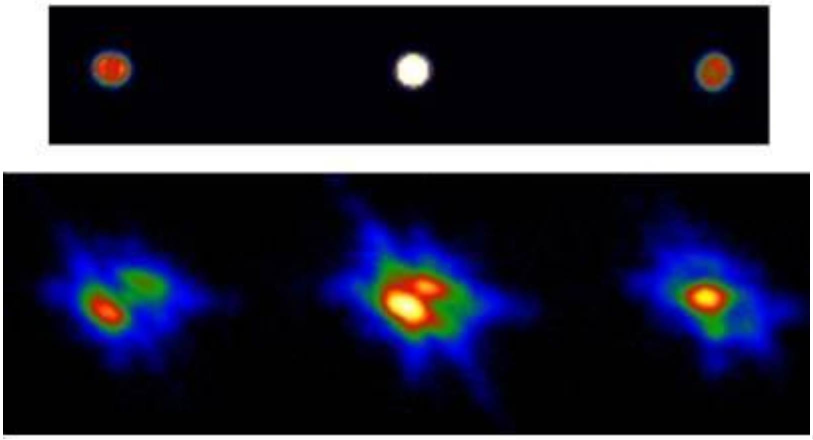

Figure 1: Top: Experimental nm-scaled vortices of topological charge -1, 0, and 1. Bottom: After mode convertsion, they appear as Hermite-Gaussian modes of order -2, -1, and 0, allowing discrimination of vorticity.

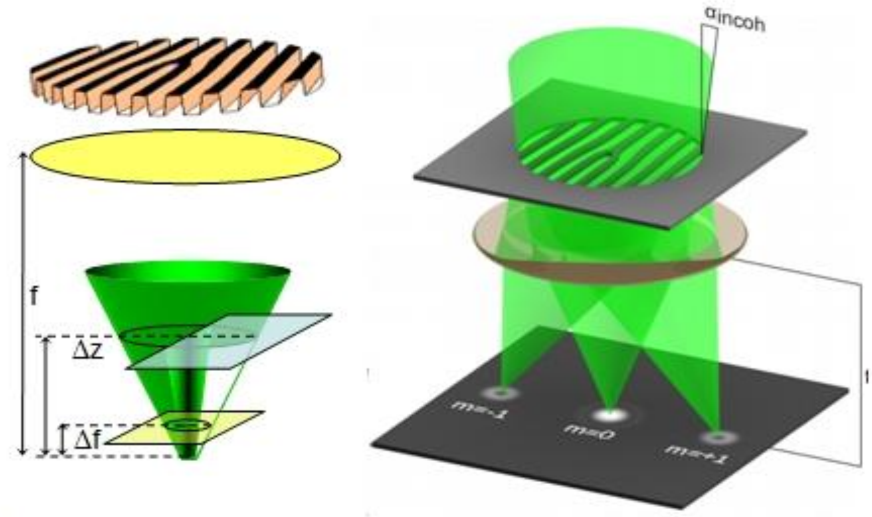

Figure 2. Sketch of the geometry (not to scale). Left: Holographic mask and lens (yellow) create a vortex in the back focal plane. The observation plane (light yellow) is slightly above the vortex for easier measurement and to minimize Gouy rotation from focus variations. A sharp edge far from the focus blocks half of the converging cone. The z-position of the knife is varied in order to see the quantized rotation. Right: Creation of a line of vortices with fundamental modes (the higher topological orders are not shown).

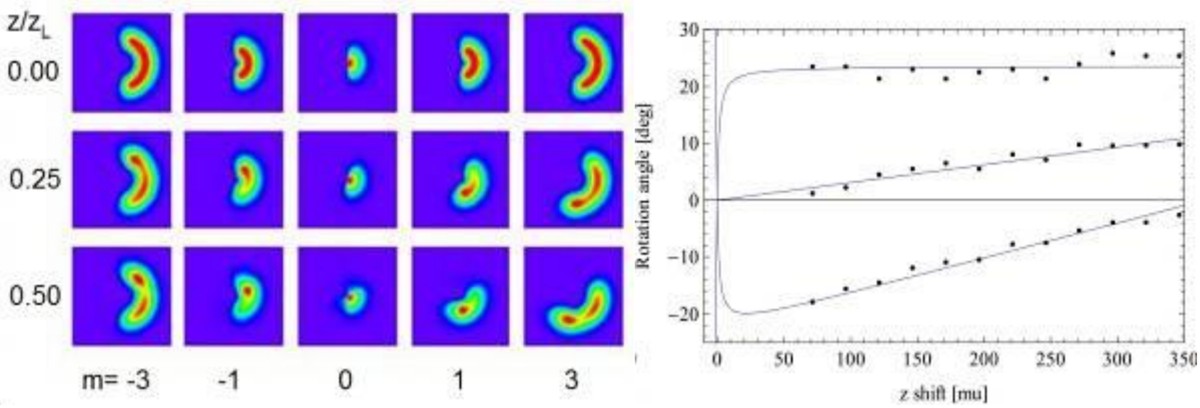

Figure 3. Left: Wave mechanical simulation of a series of cut vortices of angular momentum quantum numbers = -3 to m = 3 after a propagation distance of 0 to 0.5 Larmor lengths from the cutting edge. Rotations with zero, Larmor (for m=0) and cyclotron frequency are seen. Right: Measured rotation angles of vortices m = 3 (lowest data set), m = 0 (middle set) and m = -3 (upper set), as a function of the position z of the blocking edge. The curves are theoretical predictions.