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Realization of the Ehrenberg-Siday thought experiment –interaction-less electron microscopy

A. H. Tavabi[1,2], C. B. Boothroyd[3], E. Yücelen[4], R. Dunin-Borkowski[1,2], S. Frabboni[5,6], G. C. Gazzadi[5]
G. Pozzi[7,1]

[1]Forschungzentrum Jülich, Ernst Ruska-Centre for Microscopy and Spectroscopy with Electrons, Jülich, Germany
[2]Forschungszentrum Jülich GmbH, Peter Grünberg Institute, Jülich, Germany
[3]Nanyang Technological University, School of Materials Science and Engineering, Singapore, Singapore
[4]FEI Company, Eindhoven, Netherlands
[5]University of Modena and Reggio Emilia, Department FIM, Modena, Italy
[6]CNR-Institute of Nanoscience-S3, Modena, Italy
[7]University of Bologna, Department of Physics and Astronomy, Bologna, Italy

a.tavabi@fz-juelich.de

In 1949, Ehrenberg and Siday observed that the expression for the electron-optical refractive index contains the vector potential and not the magnetic field strength, concluding that one might expect wave-optical phenomena to arise which are due to the presence of a magnetic field but not due to the magnetic field itself, i.e., which arise whilst the rays are in field-free regions only [1]. Here, we realize an experiment, whereby a magnetic flux that should result in a detectable phase shift is placed in the geometrical shadow between two interfering electron beams in a two-slit experiment. The magnetic flux is generated by a uniformly-magnetized Co nanorod of constant cross-section deposited between the slits. The Co nanorod has a negligible magnetic stray field, arising only from the closure field associated with its finite length (Fig. 1).
The presence of a magnetic flux between the slits is difficult to identify in a recorded interference pattern unless its magnitude or direction changes and differences between images are compared. In a first series of experiments, the specimen containing the slits and the Co nanorod was tilted about a horizontal axis, which was in the specimen plane and perpendicular to the lengths of the slits and the nanorod. The conventional electron microscope objective lens was used to apply a vertical magnetic field to the specimen while it was being tilted, in order to change the direction in which the Co nanorod was magnetized while observing the interference pattern. Figure 2 shows the result of this experiment. Although there are small shifts in the position of the pattern, the images shown in Figs 2(b) and 2(c) are clearly in registry, as are those in Figs 2(d) and 2(e). A phase shift of approximately , which can be seen between the patterns in (c) and (d), results from a reversal in the magnetization direction of the Co nanorod at a specimen tilt angle of approximately -5°. Intensity profiles generated from the Fraunhofer patterns in (c) and (d) are overlaid onto each other in Fig. 2(f) for specimen tilt angles of -4° (blue) and -6° (red).
The recorded phase shift can be used to study changes in the magnetic flux of the Co nanorod when its magnetic state is switched, despite the fact that the electron passes only through a field-free region: an example of interaction-less electron microscopy.

References:
[1] W. Ehrenberg and R. E. Siday, The refractive index in electron optics and the principles of dynamics Proc. Phys. Soc., Sec. B 62: 8–21, 1949.
[2] G. Pozzi, C. B. Boothroyd, A. H. Tavabi, E. Yücelen, R. E. Dunin-Borkowski, S. Frabboni and G. C. Gazzadi, Experimental realization of the Ehrenberg-Siday thought experiment Appl. Phys. Lett. 108: 083108, 2016.

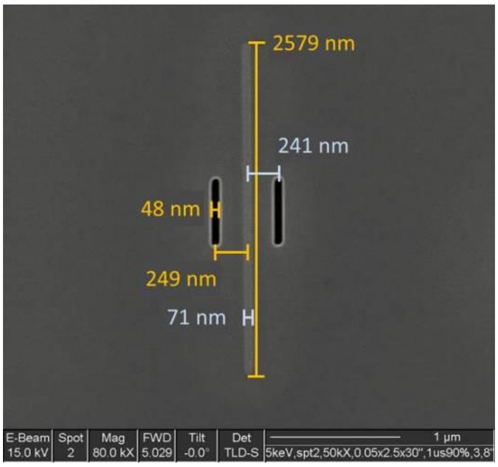

Figure 1. Secondary electron image of the two slits and the Co nanorod. The slits are the dark features on either side of the Co nanorod.

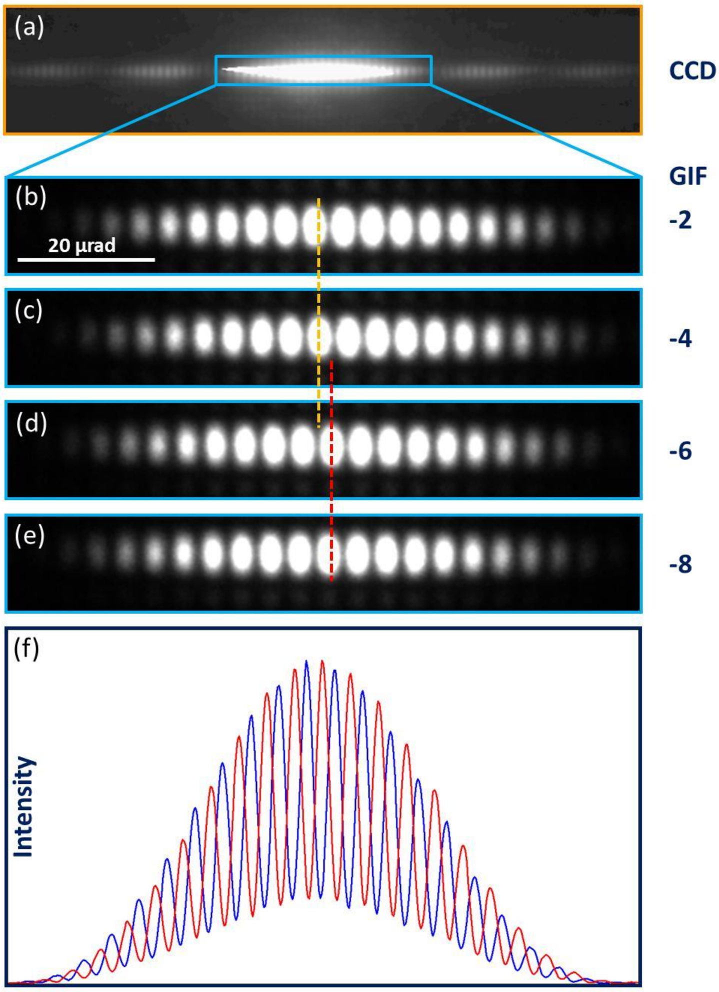

Figure 2. (a) Low-angle electron diffraction image recorded using a conventional charge-coupled device (CCD) camera located before the Gatan imaging filter (GIF). (b)–(e) Low-angle electron diffraction images recorded using the GIF CCD camera after tilting the sample between -2° and -8° in steps of -2°. (f) Line scans of (c) in blue and (d) in red.