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Electron Vortex Beams for Magnetic Measurements on Ferromagnetic Samples via STEM

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X-ray magnetic circular dichroism is a well-established method to study element specific magnetic properties of a material, while electron magnetic circular dichroism (EMCD), which is the electron wave analogue to XMCD, is scarcely used today. Recently discovered electron vortex beams, which carry quantized orbital angular momenta (OAM) L, promise to also reveal magnetic signals [1]. Since electron beams can be easily focused down to sub-nanometer diameters, this novel technique provides the possibility to quantitatively determine local magnetic properties with unrivalled lateral resolution. In order to generate the spiralling wave front of an electron vortex beam with an azimuthally growing phase shift of up to 2π and a phase singularity in its axial centre, specially designed apertures are needed [2]. Dichroic signals on the L_2 and L_3 edge are expected to be of the order of 5% [3,4].

For this purpose, we have successfully implemented two types of apertures (spiral- and fork-type, see Fig. 1) into the condenser lens system of a FEI Titan[3] 80-300 transmission electron microscope (TEM) equipped with an image spherical aberration corrector. The spiral aperture allows for the generation of focused electron vortex beams with user-selectable OAM that can be used as probes in scanning TEM (STEM). Since for such spiral apertures, the different OAM are dispersed along the beam direction, tuning the focal length of the condenser lens allows for a selection of the OAM. In the case of the fork-type aperture, the EVB are dispersed in the x-y plane.

First investigations were focused on probing the presence of an EMCD signal with such vortex beams on different thin ferromagnetic Ni [5] and Fe films and on hard magnetic $L1_0$ ordered FePt nanocubes. Here, the diameter of the L = 0 probe (= full with at half maximum, FWHM) is 0.14 nm, whereas the |L| = 1 probes have diameters of roughly 0.3 nm.
However, first experiments did *not* reveal any differences in the absorption edges in the electron-energy-loss spectra (EELS) generated by vortex beams with different OAM (cf. Fig. 2).

In order to understand the lack of any dichroic signal when using spiral apertures, the generation and propagation of the vortex wave function and the spatial distribution of the OAM were simulated for the given experimental setup. The simulations reveal that although the OAM is largely localized (in all three dimensions) symmetrically around the geometrical focal points, the superposition of the selected vortex state (e.g., L = +1) with contributions from adjacent vortex states (e.g., L = 0 and L = -1) results in a suppression of the total OAM [5].

We have recently devised an escape route to this problem by blocking any partial beams that carry other but the desired OAM prior to the interaction of the beam with the ferromagnetic sample. This is achieved by using a special condensor aperture in combination with a fork-type aperture to select a single partial beam with the chosen OAM. This approach allows to generate atom-sized EVB with probe diameters of 0.3 nm and a well-defined OAM. Although this discretization results in an increased signal-to-noise ratio, this novel technique allows for atomic resolution EELS measurements. First experiments using this new optical setup show very promising EMCD results on ferromagnetic FePt nanoparticles.

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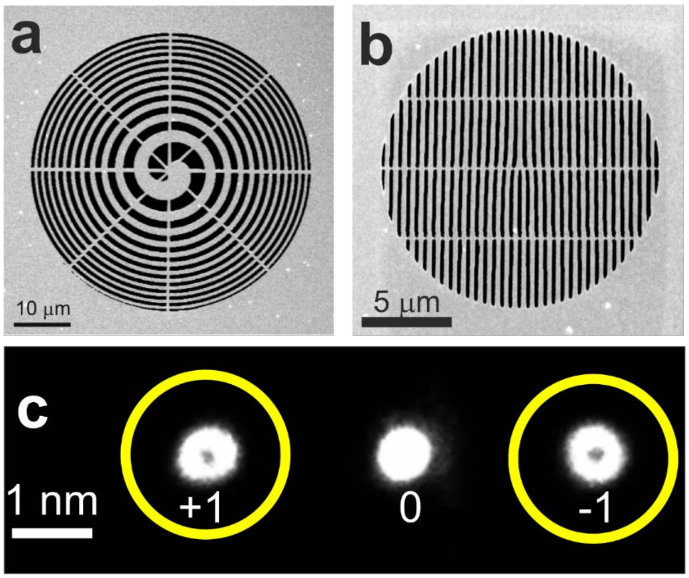

Fig 1: Generation of electron vortex beams. a, Scanning electron microscope image of a spiral-type aperture. b, Scanning electron microscope image of a fork-type aperture. c, Image of the electron beam that is generated by the fork-type aperture in b. Yellow circles mark the area of the inserted additional aperture that is used for the generation of single EVB.

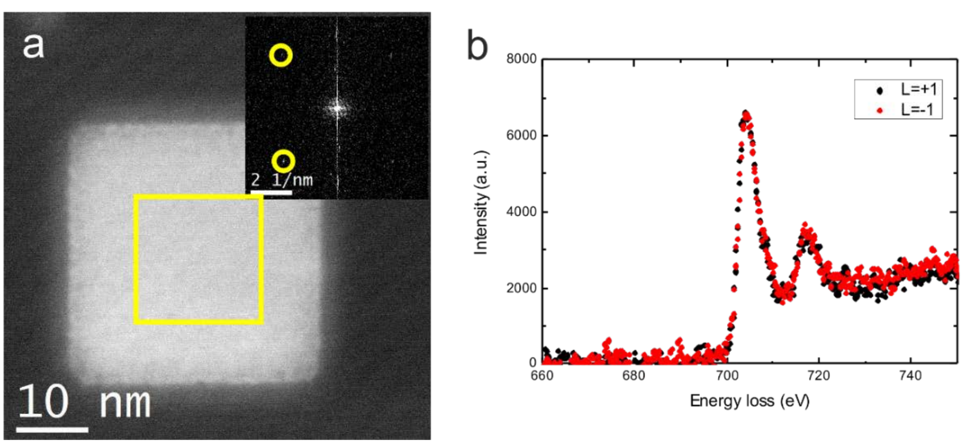

Fig 2. Magnetic measurements using a spiral-type aperture at FePt nanocubes. a, Scanning dark-field image of a FePt nanocube acquired with the L=0 beam of the spiral-type aperture. Inset show FFT with marked superstructure reflections of $L1_0$-ordered FePt. b, EEL spectra acquired with an EVB scanned over the yellow marked area in b. *No* significant EMCD signal (= difference between the two spectra) is observed.