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Progress in vortex filter EMCD: Experimental evidence and sub-nanometre resolution

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Soon after the inception of electron energy-loss magnetic chiral dichroism (EMCD) (1), an intimate connection to the orbital angular momentum (OAM) of the probing electron has been put forward (2). In inelastic scattering processes in magnetic materials, a chiral electronic transition transfers OAM in units of from the beam to the probed atom, producing atom-sized electron vortex beams (EVBs) (3).

In this work, new evidence will be given that holographic vortex masks (HVMs), typically used to impart OAM to electrons, can be employed in an imaging STEM-like geometry (Fig.1a), to filter the outgoing inelastically scattered electrons for their OAM content, i.e. to yield an EMCD signal. This approach neither relies on the standard EMCD geometry and the specimen"s role as a beam splitter nor does it require a tedious crystal alignment. The difficulties of this approach were already pointed out in (4). Here, a simplified setup and the improvement of the SNR will be addressed.

Experiments were done on a Titan Holo at the ER-C equipped with a wide-gap polepiece, where a 40 µm phase HVM was inserted in the objective aperture holder. Additional experiments using the setup given in (4) with a 30 µm binary absorption HVM were done on a Tecnai F20. The samples were sputtered 30 nm Fe films on SiNx-membranes and cross-sections of a FeRh layer. Our in-house inelastic multi-slice simulation (IMS) code was used to estimate the EMCD signal and incoherent source size broadening (ISSB) effects.

Fig.1b shows rotationally averaged radial profiles of the energy-filtered EVBs after passing 30 nm Fe and careful astigmatism and defocus control. The difference signal, $IDiff=2\,(I_+(r)-I_-(r))/(I_+(r)+I_-(r))$, where $I_\pm(r)$ are the respective EVBs" radial profiles for $m=\pm1$, can be reproduced using IMS, showing sub-nanometre spot size. A reversal of $IDiff(r)$ can be observed for the L2-edge, see Fig.1c. Fig.1d and e were taken on a FeRh alloy at 450K. Upon magnetisation reversal, the difference signal changes its sign accordingly. Atomic scale IMS mappings show a significant variation of *IDiff* over the unit cell (Fig.2).

Experiments on different machines and samples show difference signals that fit well to IMS with improved SNR. Signal reversals between the L3 and L2-edges, as well as for parallel and antiparallel magnetisation were observed, hinting at a faint EMCD signal. Sub-nanometre resolution could be achieved and IMS mappings suggest that even atomic resolution should be feasible using Cc corrected machines and improved HVMs.

References:

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Fig. 1: a) Experimental setup of vortex filter EMCD. (b) Rot. avg. of m=±1 EVBs at 710eV, 10eV slit, measured at the Titan Holo at 300kV on 30nm Fe and df~0nm, with IDiff curves and the IMS simulation for an ISSB of 0.4nm. (c), the same as (b) but for the L2-edge. (d), the same as (b) but for 50nm FeRh at parallel and (e) anti-parallel lens field, taken at the Tecnai.

Fig. 2: Vortex filter EMCD IMS maps of IDiff over a bcc-Fe unit cell including ISSB, computed for t=30nm and α=7mrad, ß=5mrad, Cs=2.7mm, U=300kV, df=73nm and ISSB=0.1nm. Green circles represent the Fe-atoms.

Fig. 1

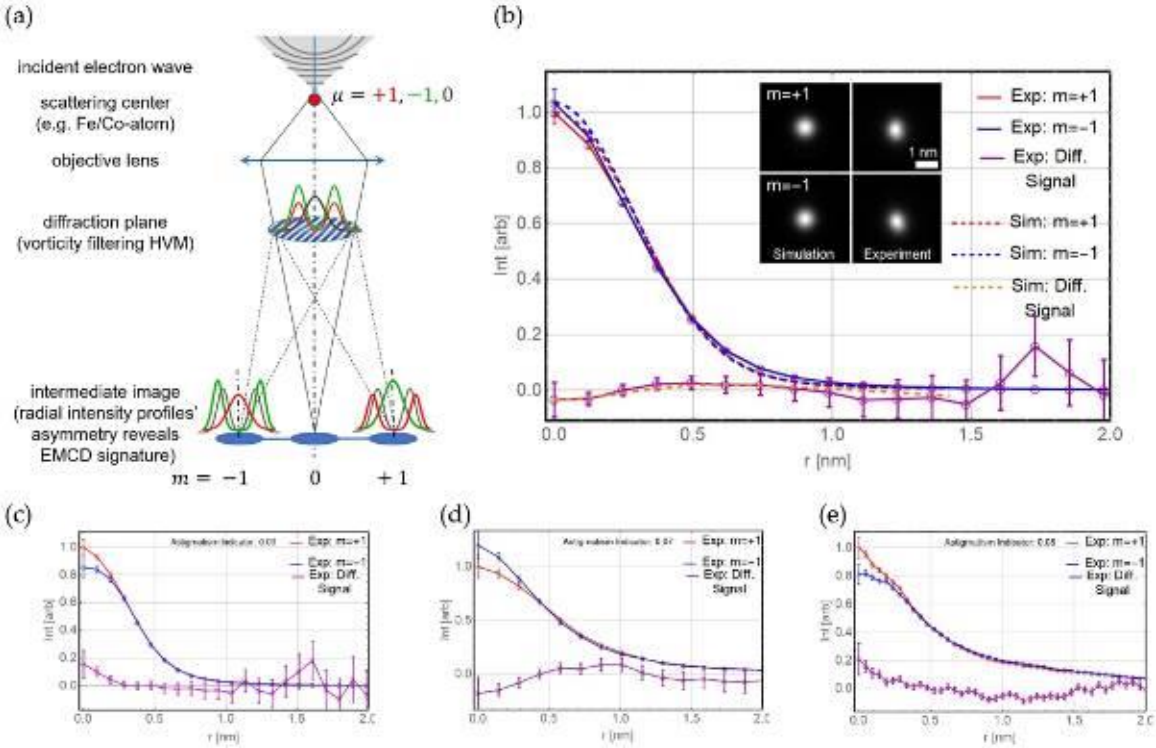

Fig. 2