Electron magnetic circular dichroism: state of the art and future prospects

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Progress in nanotechnology requires modern characterization tools with sufficient spatial resolution. Transmission electron microscopy (TEM) is a natural method of choice, routinely allowing measurements at nanometer scale or even at atomic lateral resolution - thanks to the aberration correctors, which allow to focus electron beams to areas with diameter smaller than an Ångström. Within the field of magnetic studies, one typically applies Lorentz microscopy and holography methods. An alternative measurement method in development is electron magnetic circular dichroism (EMCD; [1]), which is an electron microscopy analogue of the well-established method utilizing circularly polarized x-rays, the x-ray magnetic circular dichroism (XMCD). EMCD is a special case of electron energy loss spectroscopy (EELS) of core-level excitations - EMCD spectrum is obtained as a difference of two EELS spectra measured under specific conditions. Similarly as XMCD, also EMCD is quantifiable using sum rules [2,3], which allow to access the spin and orbital magnetic moments of studied elements. While XMCD is limited by the beam size to spatial resolutions of approximately 10nm, EMCD has a potential to reach atomic resolution.

EMCD went through a rapid development in terms of theoretical understanding, improvements of spatial resolution and signal to noise ratio. Recently EMCD spectra were extracted using scanning TEM with atomic size electron beams from areas as small as few square nanometers [4,5,6]. In an alternative setup utilizing chromatic and geometric aberration correction a quantitative EMCD has been measured from single atomic planes [7]. In addition, there are high expecations from scanning TEM measurements with electron vortex beams [8] with atomic size [9], which should provide higher signal to noise ratios per unit of beam current [10].

In general, EMCD, as a difference of two EELS spectra, requires high signal to noise ratios to be quantifiable. Strength of EMCD is influenced by the strong interaction of electrons with the crystal lattice - the dynamical diffraction effects. Therefore theory and simulations play a strong role in designing EMCD experiments. Similarly, post-processing the aquired datasets plays a crucial role. Utilizing modern methods of data analysis, such as tensor decomposition methods [11] and local low-rank denoising [12] help to identify weak signal components in large datasets. We will review the state of the art of EMCD in both theory and experiment, and provide some visions for the future, such as three-dimensional magnetic studies combining scanning TEM with depth sectioning, or automatization of the selection of experimental geometries.

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[1] P. Schattschneider *et al.*, Nature **441**, 486 (2006).

[2] J. Rusz, O. Eriksson, P. Novak, P. Oppeneer, Physical Review B **76**, 060408(R) (2007).

[3] L. Calmels *et al.,* Phys. Rev. B **76**, 060809(R) (2007).

[4] J. C. Idrobo *et al.*, Advanced Chemical and Structural Imaging **2**, 5 (2016).

[5] J. Rusz *et al.*, Nature Communications **7**, 12672 (2016).

[6] T. Thersleff, J. Rusz, B. Hjörvarsson, K. Leifer, Physical Review B **94**, 134430 (2016).

[7] Z. Wang *et al.*, Nature Materials **17**, 221 (2018).

[8] J. Verbeeck, H. Tian, P. Schattschneider, Nature **467**, 301 (2010).

[9] J. Rusz, S. Bhowmick, Physical Review Letters **111**, 105504 (2013).

[10] D. Negi, J.-C. Idrobo, J. Rusz, Scientific Reports, in press (2018).

[11] J. Spiegelberg, J. Rusz, K. Pelckmans, Ultramicroscopy **175**, 36 (2017).

[12] J. Spiegelberg *et al.*, Ultramicroscopy **187**, 34 (2018).